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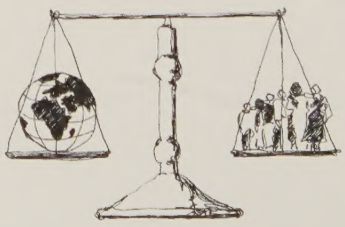

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Forum: Call-for-Commentaries for 'The potassium paradox: Implications for soil fertility, crop production and human health' by S.A. Khan, R.L. Mulvaney and T.R. Ellsworth

Renewable Agriculture and Food Systems encourages the constructive exchange of ideas and perspectives among scientists, practitioners and industry on new and potentially controversial topics in agriculture and food production through our open discussion Forum. The current Forum addresses the use and efficacy of standard soil fertility tests for recommending fertilizer application rates, specifically with regard to soil potassium (K) management. In 'The potassium paradox: Implications for soil fertility, crop production and human health' by S.A. Khan, R.L. Mulvaney and T.R. Ellsworth, the authors posit that standard soil test K (STK) methods are of limited interpretive value due to spatio-temporal variations in soil K dynamics. Further, the authors challenge whether the use of STK and routine K applications as KCl result in improved crop yields in the context of the 'build-and-maintain' approach to soil K fertility. Although several experts were contacted but declined to contribute commentary in response to this topic at this time, the findings and issues raised by Khan et al. are of wide interest and present an opportunity for discussion.

We invite our readers to contribute their comments to our discussion Forum on 'The potassium paradox: Implications for soil fertility, crop production and human health' and on the unique challenges of managing soil K fertility. Please submit your commentaries using the *Renewable Agriculture and Food Systems* on-line Editorial Manager by 17.00 hours EST on May 31, 2014 (http://www.editorialmanager.com/rafs/). Your commentary, if selected among those submitted and evaluated through peer-review, will be published together with responses from Khan et al. in an upcoming volume of *Renewable Agriculture and Food Systems*. Our journal values the discussion of important agricultural and food production issues from a diversity of viewpoints. Opinions published in the Forum and responses, however, are solely those of the authors and do not necessarily reflect the opinions of journal editors or Cambridge University Press.

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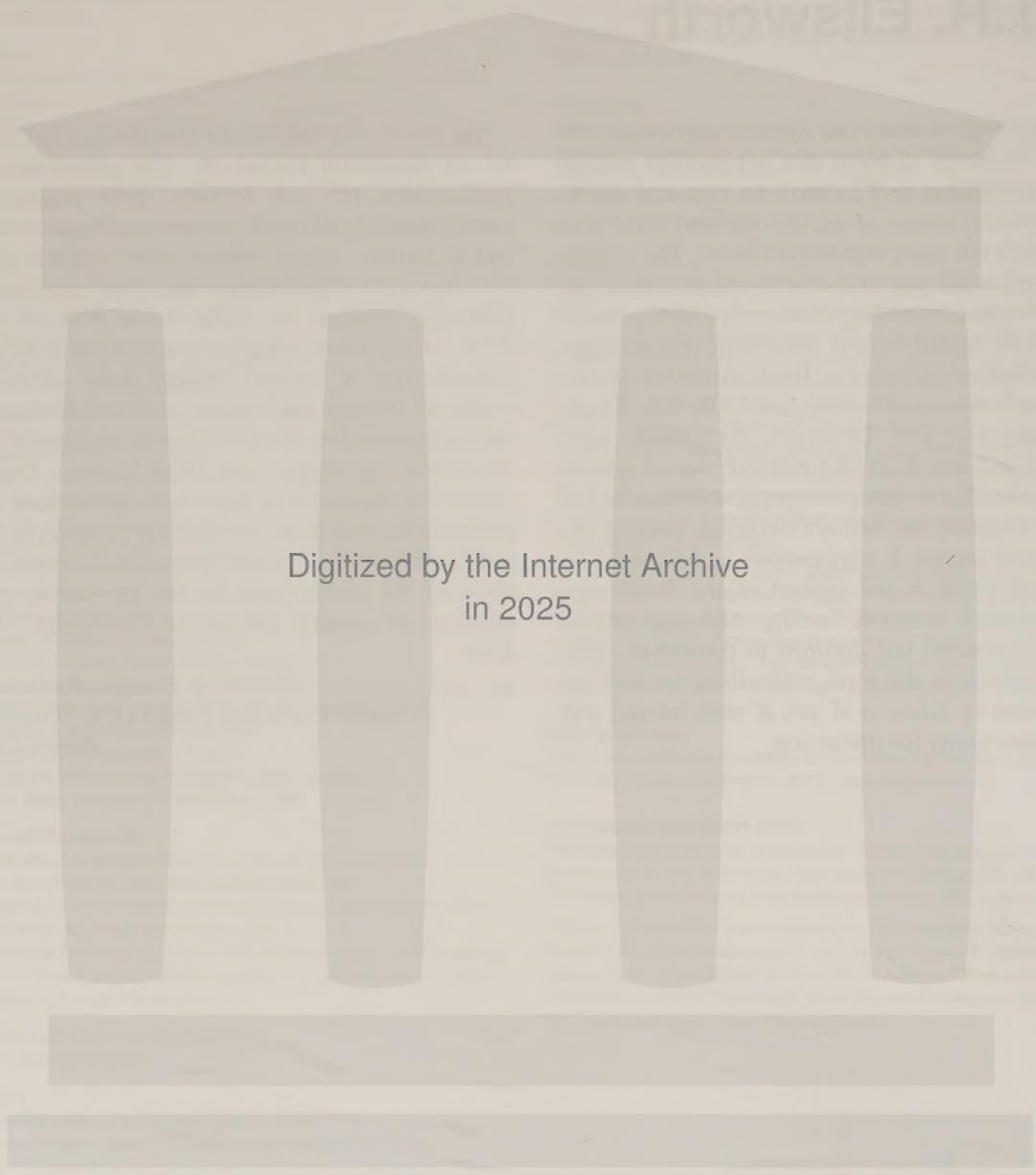

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The potassium paradox: Implications for soil fertility, crop production and human health

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Abstract

Intensive fertilizer usage of KCl has been inculcated as a prerequisite for maximizing crop yield and quality, and relies on a soil test for exchangeable K in the plow layer to ensure that soil productivity will not be limited by nutrient depletion. The interpretive value of this soil test was rigorously evaluated by: (1) field sampling to quantify biweekly changes and seasonal trends, (2) characterizing the variability induced by air drying and the dynamic nature of soil K reserves and (3) calculating the K balance in numerous cropping experiments. These evaluations leave no alternative but to question the practical utility of soil K testing because test values cannot account for the highly dynamic interchange between exchangeable and non-exchangeable K, exhibit serious temporal instability with or without air drying and do not differentiate soil K buildup from depletion. The need for routine K fertilization should also be questioned, considering the magnitude and inorganic occurrence of profile reserves, the recycling of K in crop residues and the preferential nature of K uptake. An extensive survey of more than 2100 yield response trials confirmed that KCl fertilization is unlikely to increase crop yield. Contrary to the inculcated perception of KCl as a qualitative commodity, more than 1400 field trials predominately documented a detrimental effect of this fertilizer on the quality of major food, feed and fiber crops, with serious implications for soil productivity and human health.

Key words: soil K testing, soil K reserves, residue K recycling, KCl, potash fertilizer, agricultural sustainability, Cd bioaccumulation, Morrow Plots

Introduction

In the modern era of industrialized agriculture, there is a prevalent view of intensive fertilizer inputs as a prerequisite for maximizing yield, and hence short-term profitability. Unfortunately, several decades of these inputs can have unintended consequences for the chemical, physical and biological functioning of the soil resource, and for air, water and food quality[1–3].

Implicit to intensive K fertilization is the bank account philosophy of managing soil fertility, which emphasizes the need for fertilizer inputs to at least replace crop removal[4]. According to this philosophy, a major rationale for K fertilization is to maintain soil reserves without regard to the economic importance of yield response[5–7] or the overwhelming abundance of mineral K in most arable soils and subsoils, especially those dominated by 2:1 minerals[8–12]. These reserves were recognized long ago for their fundamental role in supplying K for plant uptake, such that K fertilization was considered unnecessary when residues were returned to the soil[8,9]. With the entry of Canadian KCl into the world fertilizer market in the 1960s, the traditional approach to indigenous K fertility was displaced by growing reliance on a commercialized input.

Fertilizer K management originally utilized the sufficiency concept to predict yield response from exchangeable K in the plow layer[13]. An implicit assumption is that soil testing, typically carried out once in a 4-year interval, can adequately represent profile supplies of plant-available K. This assumption, no less relevant to the basic cation saturation ratio concept[14–16], is highly questionable in view of evidence that the exchangeable fraction is in a highly dynamic and temporally variable equilibrium with a vast storehouse of non-exchangeable and mineral K[10,17–21] (see also supplemental references [1–3] for the online version of the paper). Since the 1970s, excessive K usage has been further intensified by the buildup-maintenance concept that inflates fertilizer consumption under the pretext of preventing yield reduction, and thus accentuates the economic interests of the fertilizer industry over those of the producer[6,7].

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Under the latter concept, the sole purpose of soil K testing is to quantify fertilizer inputs for building up exchangeable K to a critical level that precludes the possibility of yield response, while still more K is prescribed as maintenance to replace annual crop K removal.

To ascertain whether the usual approach for exchangeable K testing, with or without air drying, provides a reliable basis for fertilizer K management, the work reported herein was conducted to quantify: (1) temporal and seasonal variability in K test values obtained through biweekly sampling of surface soil with no recent history of KCl fertilization; (2) K test changes induced by air drying soils that differed in long-term KCl inputs; (3) non-exchangeable K released by successive extraction; (4) K balance in relation to soil K test changes for cropping experiments with static fertilizer K inputs; and (5) the fertilizer value of KCl in a systematic survey of peer-reviewed and university publications that encompass a global range of soil types, cropping practices and management systems in production settings. Based on these evaluations and the recycling of K from crop residues, we tested the null hypotheses that: (1) the usual approach to soil K testing is of no value for predicting fertilizer requirement or monitoring changes in K fertility, and (2) KCl fertilization will seldom lead to economic yield response or improve crop quality.

Materials and Methods

Seasonality study

To characterize seasonal changes in K test values, soil samples were collected at biweekly intervals between mid-March 1986 and 1990, from the University of Illinois South Farm at Urbana, IL. As detailed by Khan[22], this sampling was done from six plots in a K rate study on a Drummer silty clay loam, classified as a fine-silty, mixed, superactive, mesic Typic Endoaquoll with montmorillonite and illite as the major 2:1 clay minerals[23]. The plots, each measuring 6 m wide and 24 m long with <1% slope, had been used as a corn (*Zea mays* L.) breeding nursery cropped in alternate years to soybean (*Glycine max* L. Merr.), and had been fertilized annually with KCl from 1970 to 1983, at rates of 0, 46, 93, 139, 186 and 232 kg K ha^{-1}. Of the six plots sampled by Khan[22] for the seasonality study, the sole focus herein is on the plot that received no fertilizer P or K, but only a spring application of 160–180 kg N ha^{-1} as NH_4NO_3 when corn was grown between 1970 and 1990. Sampling followed a fixed protocol involving: (1) manual use of either a 2.5-cm diameter probe or an auger; (2) care to avoid previous sampling points; and (3) collection of a five-core composite (0–18 cm) from each of three locations representing northern, central and southern subplots. The composite samples, in polyethylene bags, were immediately transported to the laboratory, passed through a 4.75 mm screen and thoroughly homogenized. Triplicate 1.2-g subsamples were analyzed for field-moist exchangeable K following the ammonium acetate ($NH_4C_2H_3O_2$)-extraction technique described by Knudsen et al.[24], using a Jenway Model PFP 7 flame photometer (Jenway, Essex, UK). So as to express these analyses on an air-dry basis, soil moisture content was determined by air drying two additional 1.2-g subsamples for 48 h in a forced-air oven at 40°C. The remaining soil was transferred to a paper bag and subsequently air dried in the same oven for 10 days. The dried soil was crushed with a rolling pin to pass a 2 mm screen, mixed thoroughly in the bag and analyzed within 1 day for air-dried exchangeable K.

Drying study

The effect of soil moisture level on the release of exchangeable K was investigated for the Drummer soil at Urbana where the seasonality study was conducted. After harvest in October 1989, a five-core composite was collected with a 2.5-cm diameter soil probe to a depth of 18 cm at three locations within each of the four plots where the annual K rate had been 0–139 kg ha^{-1}, and the 15 cores collected from each plot were composited in polyethylene bags. The samples were transported to the laboratory, screened while field-moist to pass through a 4.75 mm sieve and spread to a depth of 2.5 cm on wooden trays. The trays were placed on laboratory benches for drying at approximately 20°C and 64% relative humidity, while air was continuously circulated across the samples that were periodically homogenized to ensure uniform moisture content. At 3-h intervals, triplicate samples from each tray were analyzed for moisture content and exchangeable K (expressed on an air-dried basis), until no further moisture loss was observed after 33 h. These analyses were also performed on a portion of each air-dried sample that had been oven-dried at 105°C. The percentage increase in exchangeable K upon air drying was calculated as $100 \times (K_{AD} - K_{FM})/K_{FM}$, where the field-moist (FM) value was obtained at the initial soil moisture content and the air-dried (AD) value corresponds to a moisture content of approximately 40 g kg^{-1}.

Speciation study

Biweekly soil samples (0–18 cm) collected and air dried for the seasonality study in August and September were composited each year between 1986 and 1989 to represent the plot that had received N but no P or K fertilization since 1970. Following 1 M $NH_4C_2H_3O_2$ extraction to determine exchangeable K, six successive digestions were performed to liberate non-exchangeable K with boiling 1 M HNO_3[24]. The digests were centrifuged, and the supernatant was analyzed for K by flame photometry as described previously.

Total K analyses were performed on samples composited from 1986 and 1989, by fusion of an oven-dried (105°C) portion with $LiBO_2 \cdot 8H_2O$ in a Pt crucible[25].

The fused sample was dissolved in 0.04 M HNO_3 and analyzed by atomic emission spectroscopy using a Perkin Elmer Model 3110 spectrometer (Perkin Elmer, Norwalk, CT) and an air-C_2H_2 flame.

Morrow Plots potassium balance study

To ascertain whether the conventional approach to soil K testing reflects net K balance, exchangeable K was determined for surface (0–15 cm) samples collected in 1955 and 2005 from the Morrow Plots, where the world's longest continuous cropping experiment on the most productive soil order (Mollisols) has been conducted since 1876. The samples used in our work represent six unreplicated subplots currently designated as 3NA and 3NB under continuous corn, 4NA and 4NB under a 2-year rotation of corn and oats (*Avena sativa* L.) or soybean (since 1967) and 5NA and 5NB under a 3-year rotation of corn, oats and alfalfa (*Medicago sativa* L.) hay, where B- but not A-series subplots receive NPK fertilization that supplied 28–186 kg K ha^{-1} in some but not all years. The soil is classified as Flanagan silt loam, a fine, smectitic, mesic Aquic Argiudoll with illite and smectite as the dominant 2:1 clay minerals[26]. Further details concerning the Morrow Plots and their management can be found in Khan et al.[27].

A baseline for the study period was established using air-dried soil samples collected in the spring of 1955 prior to any application of KCl, which were obtained from an archival collection maintained by the University of Illinois in individually labeled air-tight glass containers. The 2005 samples consisted of triplicate soil cores that were collected just after harvest, air dried at 40°C and screened to <2 mm. Analyses for exchangeable K were performed in triplicate as described previously, by processing all samples in a single batch. To allow expression on a mass basis (kg ha^{-1}), test values were multiplied by the corresponding bulk density, obtained from direct measurements in 2005, or by using pedotransfer functions to estimate 1955 values. A more detailed description is available in Khan et al.[27].

A K balance was constructed for 1955–2005, based on cumulative fertilizer input and crop removal. Morrow Plot records were utilized to document KCl inputs, whereas crop K removal was estimated using composition data from the Illinois Agronomy Handbook[28] in conjunction with yield and management records. The handbook values used for crop K composition are typical of university maintenance recommendations to replace K removed in alfalfa hay (20.8 kg Mg^{-1}) or by corn (4.2 kg Mg^{-1}), soybean (18.0 kg Mg^{-1}) and oats (5.2 kg Mg^{-1}) harvested for grain. The yield records used were expressed as dry tons $acre^{-1}$ for alfalfa, or as bushels $acre^{-1}$ at a market-standard moisture content of 155 g kg^{-1} (15.5%) for corn (56 lb $bushel^{-1}$), 130 g kg^{-1} (13%) for soybean (60 lb $bushel^{-1}$) and 140 g kg^{-1} (14%) for oats (32 lb $bushel^{-1}$). In the case of the unfertilized (NA-series) subplots, crop K removal was intensified by the harvest of corn or oats stover until 1967, estimated at 331 kg K ha^{-1} for continuous corn, 310 kg K ha^{-1} for the corn–oats rotation, and 256 kg K ha^{-1} for the corn–oats–hay rotation. To account for K removal in these residues, a harvest index of 0.5 was assumed for both crops[29–32], and a K concentration of 13.5 (corn) or 15 (oats) kg Mg^{-1} of dry matter[33].

Potassium balance for other studies

In a more comprehensive evaluation of exchangeable K testing for air-dried soil, a systematic review of the literature was performed to compile a global database of short- and long-term K response experiments involving fixed (static) fertilizer treatments and representing a wide range in soils, cropping and management practices. This review utilized the CAB citation index and reviews of relevant individual journals. Three attributes were critical in selecting these data sets: (1) soil test values for exchangeable K determined at the beginning and end of the study period; (2) fertilizer K inputs throughout the study period; and (3) yield or K removal data for all crop material harvested. In cases where soil K test data were reported as a mass-based concentration, a conversion was made to kg ha^{-1} assuming a bulk density of 1.47 Mg m^{-3}, which corresponds to the conventional weight of 2 million pounds (907 Mg) per acre (0.405 ha) for a plow layer 6 inches (15 cm) deep. When necessary, crop K removal was calculated from yield data by utilizing published K concentrations for grain[28] and/or stover[33].

Fertilizer value of potassium chloride

To ascertain the benefits of KCl fertilization for crop yield and quality, an extensive effort was made in surveying peer-reviewed and university data from published field studies not exceeding 10 years in duration. For the yield survey, 211 publications reporting statistical analyses of yield differences were utilized in calculating percentage response to KCl fertilization as 100 × (fertilized yield − unfertilized yield)/unfertilized yield. Qualitative impacts of this fertilizer were evaluated as positive, negative, none or variable, according to what was reported in 139 publications comparing a specific parameter of crop quality with and without the use of KCl. Major emphasis was placed on broad coverage of the scientific literature, encompassing food, feed and fiber crops grown under various management practices on a wide range of soil types throughout the world.

An effort was also made in utilizing the scientific literature to assess the impact of KCl fertilization on two key aspects of soil productivity: cation-exchange capacity (CEC) and microbial N cycling. Interest in these topics was motivated by K^+ fixation that promotes interlayer collapse of 2:1 clay minerals, and by the inhibitory effects of KCl on biological N_2 fixation and nitrification.

Statistical analyses

Seasonality and linear trend analysis of the 4-year time series of air-dried test levels of exchangeable K ($kg\,ha^{-1}$) was evaluated statistically as described by Lovell[34]. Paired *t*-tests were performed on samples collected post-harvest in October 1989 to monitor changes in soil test K upon air drying. Exchangeable K data obtained for the Morrow Plots were analyzed statistically with PROC MIXED in SAS[35], such that the 2005 data provided a variance estimate for the standard error of mean values obtained as a five-core composite in 1955[27]. The step-down Bonferroni adjustment of *P* values[36] was performed with PROC MULTEST in SAS[35] for multiple comparison tests to evaluate net changes in exchangeable K between 1955 and 2005.

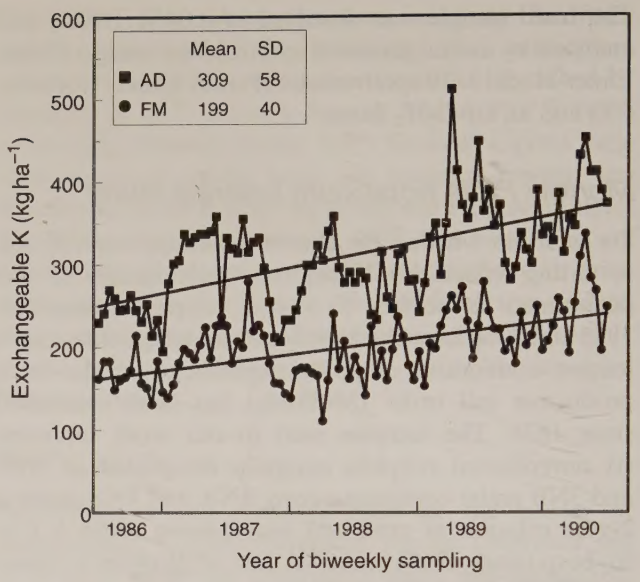

Figure 1. Biweekly changes in exchangeable K for field-moist (FM) and air-dried (AD) samples (0–18 cm) collected on 96 dates between March 13, 1986 and March 15, 1990, from a Drummer soil under a corn (*Zea mays* L.)–soybean (*Glycine max* L. Merr.) rotation. No fertilizer P or K had been applied since 1970. Data points are a mean of nine determinations representing triplicate analyses performed on five-core composites collected from each of three subplots. Trendlines were generated by linear regression. SD, standard deviation.

Results and Discussion

Evaluation of soil potassium testing

Soil testing is widely regarded as the best approach for making economical fertilizer recommendations or monitoring soil fertility changes in relation to management practices. If these objectives are to be properly met, soil sampling must be adequate to represent the field area under investigation, and test values should be calibrated to crop response and sufficiently stable that interpretations are unaffected by the time of sampling or the method of sample processing.

In the modern era of input-intensive agriculture, soil testing is often done to measure exchangeable K, following the concept originated by Bray[13]. This prevalence reflects the major emphasis given to rapid methods of sample processing and analysis in commercial soil testing, despite an inherent complication that has long been recognized: K test values can change markedly when samples are air dried to expedite processing[37,38] (see also supplemental references [4–8] for the online version of the paper). A further complication arises because of variability associated with the time of sampling[18,21] (see also supplemental references [4] and [9] for the online version of the paper), which becomes a major source of error in soil testing for site-specific management[39].

Both factors clearly contributed to the variability documented in Fig. 1 for a 4-year field study that involved biweekly sampling to monitor changes in exchangeable K test values with and without air drying. Any such changes would have been minimized because the work involved a single investigator utilizing a fixed protocol and experimental design, and a study site devoid of fertilizer K inputs for at least 14 years. By repeatedly imposing a dense sampling design on a single small research plot subject to minimal compaction from mechanical traffic, spatial variability was minimized so as to better quantify any occurrence of temporal variability.

Despite these precautions, Fig. 1 shows that soil K test levels, with or without air drying, varied drastically with the biweekly sampling strategy adopted throughout the study period, and the variation became more extensive as test values began to increase after harvest, during the usual sampling period for commercial soil testing in a temperate region such as the Midwestern USA. Statistical analyses were highly significant ($P < 0.001$) in detecting a seasonality effect on exchangeable soil K, which is consistent with several previous field studies[40,41] (see also supplemental references [10–13] for the online version of the paper) that document greater test values during the winter months. This increase can be attributed to a high soil moisture content that promotes the leaching of K from crop residues and the conversion of non-exchangeable to exchangeable K through valence dilution. After seasonality adjustment, a highly significant ($P < 0.001$) linear increase in exchangeable K was observed over the 4-year study period.

Drying was expected to decrease temporal variability by homogenizing soil samples; however, the data in Fig. 1 reveal no such effect as the coefficient of variation was nearly the same before and after air drying that escalated K test values by 55% on average. A major complication can also be found in the numerous incoherencies between field-moist and air-dried test values documented by Fig. 1, which precludes the use of a simple correction factor to compensate for air drying or the timing of sample

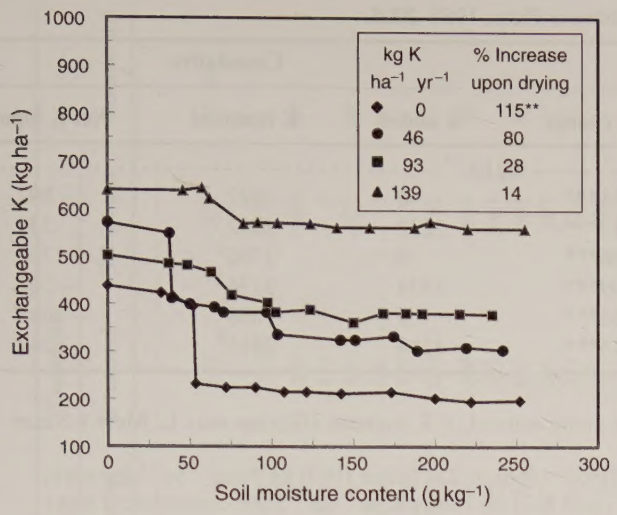

Figure 2. Potassium release curves for a Drummer soil cropped to a corn (*Zea mays* L.)–soybean (*Glycine max* L. Merr.) rotation, with or without annual application of 46–139 kg K ha^{-1} as KCl. Field-moist samples (0–18 cm) were air dried to approximately 40 g kg^{-1} in a forced-air oven at 40°C, followed by oven-drying at 105°C. Data points are a mean of triplicate determinations performed on five-core composites collected from each of three subplots. Error bars representing one standard deviation are shown, when they exceed the size of the data marker, for field-moist (FM) and air-dried (AD) test values. The percentage increase upon air drying was calculated as $100\times(K_{AD}-K_{FM})/K_{FM}$. **, significant at $P<0.01$.

collection. Both findings raise a serious concern that soil K testing by the usual approach is of no practical value, in contrast to the advocacy that is common in extension publications and presentations, trade magazines and popular articles[28,42].

The same concern emerged when sample drying was evaluated by a one-time sampling of soils that ranged widely in K fertility, so as to eliminate the confounding effect of seasonality. The results (Fig. 2) follow the usual trend toward higher test values upon air drying; however, the increase tended to be greater as the fertility level decreased, further demonstrating the difficulties inherent in correcting air-dried test values to a field-moist basis. This finding reveals that air-dried K test values can easily be misinterpreted when utilized for predicting K fertilizer requirement under low fertility management or for monitoring buildup/depletion.

A more rigorous evaluation becomes possible when soil K test data span a prolonged period documented with a complete record of K inputs and outputs. The Morrow Plots serve as an ideal resource for this purpose, providing three cropping systems that include the corn–soybean rotation common throughout the Midwestern USA. With this rotation, and also with continuous corn, K removal from the Morrow Plots occurs only in grain, whereas the intensifying effect of forage production is present with a 3-year rotation of corn, oats and alfalfa hay.

As shown by Table 1, K test levels for the surface soil were invariably increased by 51 years of cropping. Remarkably, the largest increases, highly significant at $P<0.001$, occurred in the absence of NPK fertilization, when the K balance was decidedly negative for continuous corn or the corn–oats–hay rotation. Equally remarkable is the substantial soil test increase observed for the unfertilized subplot in the two-crop rotation, despite K removal that totaled 1.4 Mg ha^{-1}. These observations are consistent with the seasonality study discussed previously (Fig. 1), which showed an upward trend over time in air-dried and field-moist K test levels in the absence of fertilizer K inputs. No less troubling are the similar net changes documented by this soil test for the three subplots receiving NPK, regardless of whether fertilizer K inputs were above (continuous corn or corn-oats-hay) or below (corn-soybean) crop removal. The implication is that the K test cannot differentiate soil K buildup from depletion.

The latter flaw is also apparent from the sheer magnitude of the K test levels reported in Table 1 for the three unfertilized subplots, particularly those under continuous corn and the corn–oats–hay rotation. By 2005, following 130 years of K removal, test values for these subplots were within the range of critical levels calibrated for North America[43], which would normally be interpreted as evidence of successful fertilizer K management.

To ascertain whether soil K testing is generally subject to the aforementioned difficulties, baseline changes in exchangeable K were compared with cumulative K balance compiled for numerous field experiments with and without K fertilization, encompassing a global range of soil orders, cropping systems and management practices. The resulting database (Table 2), consisting of 68 trials, provides no convincing evidence that soil test K reflects the net balance of K addition and removal. The most disturbing disparities involved 17 trials in which test levels were either constant or increased while crop K removal far exceeded fertilizer inputs or occurred in the complete absence of fertilization. Such obvious incongruities, paralleling what was found for the Morrow Plots (Table 1), leave little alternative but to question the validity of soil testing for exchangeable K, and this concern is especially relevant to the developing world, where soil K removal has been intensified by many centuries of grain and biomass harvest. To make matters worse, Table 2 shows that K test values sometimes decreased with a positive K balance, which according to the usual interpretation would justify unnecessary K fertilization. The implication is that soil K testing does not provide a scientific basis for fertilizer K management.

This dilemma is inherent to a one-time measurement of exchangeable K, which can never represent the highly dynamic effect of soil moisture on the interchange with vastly larger soil pools that occur in the form of non-exchangeable and mineral K[80]. The dynamic nature of soil K is no less relevant in refuting the central assumption implicit to soil K testing, namely, that plant K availability

Table 1. Soil potassium test changes and potassium balance for the Morrow Plots, 1955–2005.

Rotation[1]	Fertilizer treatment[2]	Exchangeable K[3]			Cumulative		
		Initial[4]	Final[5]	Net change	K added	K removed	Net K input
				kg ha^{-1}			
C–C	None	242 (4)	403 (33)	161***	0	892	−892
	NPK	242 (4)	354 (22)	112***	2231	1692	539
C–O(S)	None	218 (4)	304 (25)	86***	0	1706[6]	−1706
	NPK	218 (4)	327 (26)	109***	1934	2136[7]	−202
C–O–H	None	217 (6)	382 (18)	165***	0	1088[8]	−1088
	NPK	217 (6)	332 (27)	115***	3114	2865[9]	249

*** Significant at $\alpha = 0.001$ by the step-down Bonferroni procedure.

[1] C, corn (*Zea mays* L.); H, alfalfa (*Medicago sativa* L.) hay; O, oats (*Avena sativa* L.); S, soybean (*Glycine max* L. Merr.). Since 1967, the two-crop rotation has involved soybean instead of oats.

[2] NPK, nitrogen–phosphorus–potassium fertilization using urea (168 [1955–1966] or 224 [since 1967] kg N ha^{-1} yr^{-1} for corn, 28 kg N ha^{-1} yr^{-1} for oats), triple superphosphate (0–96 kg P ha^{-1} yr^{-1}) and KCl (0–186 kg K ha^{-1} yr^{-1}). No amendment was applied before 1955.

[3] Determined by $NH_4C_2H_3O_2$ extraction[24] of air-dried samples.

[4] Mean values reported from triplicate determinations of a single archived five-core composite soil sample (0–15 cm). Standard deviations shown in parentheses.

[5] Mean values reported from triplicate determinations performed on each of three replicate soil samples (0–15 cm). Standard deviations shown in parentheses.

[6] Estimated as 44% by corn, 7% by oats and 49% by soybean.

[7] Estimated as 49% by corn, 3% by oats and 48% by soybean.

[8] Estimated as 54% by corn, 25% by oats and 21% by alfalfa hay.

[9] Estimated as 26% by corn, 65% by oats and 9% by alfalfa hay.

is directly related to exchangeable K in the surface soil. Table 2 leaves no doubt that plant K uptake must originate from other sources, and is consistent with previous evidence that soil K reserves contribute considerable quantities of plant-available K[10,11,20,75,78,81–83] (see also supplemental references [14–26] for the online version of the paper).

These reserves were once recognized to be a major source of K-supplying power for the highly productive soils that dominate the Corn Belt, as well as for most other areas of the continental USA[8,9,84]. The importance of the non-exchangeable fraction as a storehouse for exchangeable and soluble K is documented by Table 3, which shows the magnitude of this fraction by six successive determinations performed on surface samples of a soil cropped for 17–20 years with no K input. Initial recoveries were three- to fivefold higher for non-exchangeable than exchangeable K, followed by a gradual decline toward a stable level of 240–300 kg ha^{-1}, with approximately 3000 kg ha^{-1} as the cumulative recovery of non-exchangeable K. The resilient behavior of soil K is further revealed, in that 4 years of crop K removal had no consistent effect on soil concentrations of exchangeable, non-exchangeable or total K, implicating the mineral fraction as an important source of buffering. These findings are to be expected, considering what has long been known about the availability and dynamics of non-exchangeable and mineral K, based on chemical extraction[19,85–87] (see also supplemental references [22] and [27–30] for the online version of the paper), exhaustive cropping[81,86,88,89] (see supplemental references [8], [15] and [16] for the online version of the paper) and electrodialysis[83,90].

The importance of non-exchangeable and mineral K for plant uptake is by no means unique to micaceous clays, which are subject to biological weathering in the rhizosphere[91–94] (see also supplemental references [28] and [31] for the online version of the paper). Sand- and silt-sized muscovite and biotite can also be a major source of plant-available K, as demonstrated conclusively by Mengel et al.[83] in studies with 14 loess-derived Alfisols. These primary minerals, and also K feldspars, are believed to account for the high K-supplying power of sandy Ultisols of the Atlantic Coastal Plain[82,95–97], while non-exchangeable K reserves can even be important for growing a shallow-rooted crop such as pineapple on the basaltic Andisols of Hawaii[81].

Soil K reserves are much greater for the profile than the plow layer[12,62,95,97,98] (see also supplemental references [32–34] for the online version of the paper), and can be more fully exploited by many agricultural crops with a well-developed rooting system. The importance of subsoil K is clearly apparent from K/Rb isotope dilution studies demonstrating that the extent of uptake is directly proportional to rooting depth[99–101]. This uptake is largely concentrated in the vegetative biomass[33,102], and enriches the surface soil when inorganic K leaches from plant shoots or residues[8,9,81,102–106] (see supplemental references [35–45] for the online version of the paper).

Table 2. Soil potassium test changes in relation to potassium balance, as reported for static plot experiments.

Location	Soil order[1]	Cropping system[2]	Study period	Sampling depth	Exchangeable K[3]			Cumulative			Reference(s)
					Initial	Final	Net change	K added	K removed	Net K input	
				cm	kg ha^{-1}						
USA											
Alabama	Ultisols (fsl_4, scl_2, sil_1)	C–Ct (7)	1954–1969	0–15	113	104	–9	0	332	−332	44–46
					113	229	115	1488	513	975	
Illinois	Mollisols (sil)	C–S (2)	1982–1987	0–18	322	335	13	0	290	−290	47
					322	476	154	334	325	9	
	Entisols (sil)	C–S	1994–1996	0–20	288	253	–35	0	325	−325	48
					316	317	1	335	330	5	
	Mollisols (sil)	C–S	1994–1996	0–20	280	283	3	0	270	−270	
					314	339	26	335	282	52	
Indiana	Mollisols (sil)	C–S–W_w–C	1964–1983	0–20	93	112	19	0	506	−506	49
					178	422	243	2790	723	2067	
Iowa	Mollisols (cl)	C–S	1976–1989	0–15	10(3)	10(3)	(0)	0	501	–501	50
					10(3)	19(7)	9(4)	1207	600	607	
	Mollisols (l)	C–S	1979–1989	0–15	40(4)	17(7)	−22(7)	0	474	−474	51
					37(2)	61(4)	24(2)	1478	481	998	
Michigan	Alfisols (ls)	C–C	1974–1982	0–22	266	260	−6	335	284	51	52
					601	598	–3	1595	276	1319	
Minnesota	Mollisols (cl)	C–C (2)	1974–1981	0–20	227	302	75	0	258	−258	53, 54
					237	315	78	372	267	105	
Missouri	Alfisols (sil)	W_s–W_s	1963–1989	0–20	400	303	−97	0	87	−87	55
		C–C	1963–1989	0–20	414	364	50	0	50	−50	
Nebraska	Mollisols (sicl)	C–C	1973–1984	0–15	598	77(3)	17(5)	156	471	−315	6, 56
					598	83(1)	23(3)	720	486	234	
New Jersey	Ultisols (l)	A–A	1953–1961	0–30	131	105	26	0	412	−412	57
					222	660	438	3357	2006	1351	
North Carolina	Ultisols (s)	Cb–Cb	1954–1965	0–15	53	9	−44	0	215	−215	58
					53	53	0	2231	2202	29	
Oklahoma	Mollisols (l)	W_w–W_w	1938–2001	0–15	508	414	−94	0	1219	−1219	59–61
					464	548	84	1843	1201	584	
Virginia	Ultisols (sil)	C_s–C_s	1966 1971	0–15	224	85	−139	0	411	−411	62
					224	124	−100	336	440	−104	
China	Inceptisols	W_w–C[4]	1990–2005	0–20	28(4)	5(3)	−23(1)	0	718	−718	63, 64
					30(3)	24(8)	–5(5)	1500	1089	411	
	Inceptisols (sl)	C–C	1993–2004	0–20	206	223	17	0	480	−480	65, 66
					206	235	29	259	650	−391	
England	Alfisols (sicl)	B–B[5]	1856–1974	0–23	313	219	−94	0	1221	−1221	67
					313	305	−8	5040	4294	746	
	Inceptisols (sl)	Sb–W_w–B	1965–1982	0–25	162	132	−30	0	580	−580	68
					162	265	102	1992	1160	832	
	Alfisols (sicl)	W_w–W_w	1966–1992	0–23	323	271	−52	0	675	−675	69
					1326	1236	−90	2430	1431	999	

Table 2. (*Cont.*)

Location	Soil order[1]	Cropping system[2]	Study period	Sampling depth	Exchangeable K[3]			Cumulative			Reference(s)
					Initial	Final	Net change	K added	K removed	Net K input	
Denmark	Alfisols (s)	W_w–Rcl–B–Gcl	1949–1972	0–20	65	52	−13	0	456	−456	70
					188	172	−15	1584	1584	0	
	Alfisols (sl)	W_w–Rcl–B–Gcl	1949–1972	0–20	98	62	−36	0	696	−696	
					152	122	−30	1584	2160	−576	
Germany	Alfisols (sil)	Rc–Ce–Ce	1914–1975	0–15	158	123	−35	0	4531	−4531	71
					158	131	−27	5127	7039	−1912	
	Mollisols (sl)	Po–P–W_s–Rc–B	1977–1984	0–20	170	179	9	0	568	−568	72
					496	448	−48	1792	1256	536	
India	Inceptisols (ls)	C- W_w–Cp[4]	1971–1996	0–15[6]	8(8)	7(0)	−1(8)	0	3952	−3952	73
					9(6)	9(8)	(2)	2860	5642	−2782	
	Alfisols	C–W_w[4]	1972–1996	0–15	194	148	−46	0	1508	−1508	74
					194	167	−27	2460	2393	67	
New Zealand	Inceptisols	A–A[4]	1971–1974	0–20	216	225	9	0	571	−571	75
					216	394	178	786	758	28	
Nigeria	Alfisols (sc_1, ls_2)	C–C[4] (3)	1966–1968	0–15	381	198	−183	0	197	−197	76
					381	228	−153	168	239	−71	
Philippines	Inceptisols (sic)	Ri–Ri	1968–1986	0–20	521	13(5)	−38(6)	0	578[7]	−578	77
					521	15(6)	−36(5)	950	759[7]	191	
	Vertisols (c)	Ri–Ri	1968–1986	0–20	209	24(9)	4(0)	0	580[7]	−580	
					209	39(3)	18(4)	950	799[7]	151	
	Vertisols (c)	Ri–Ri	1968–1986	0–20	938	57(3)	−36(5)	0	531[7]	−531	
					938	62(6)	−31(2)	950	677[7]	273	
Poland	Alfisols (ls)	Ry–Ry	1963–1995	0–25	107	200	93	0	1254	−1254	69
					320	300	−20	2574	2310	264	
		Po–B–Rcl–W_w–Ry	1963–1995	0–25	113	147	33	0	1584	−1584	
					327	363	37	2574	3069	−495	
Scotland	Spodosols (ls)	Pr–Pr[8]	1969–1998	0–15	72	20	−52	448[9]	1608	−1160	78
					55	24	−31	1969[9]	3158	−1189	

[1] Surface texture designated parenthetically as c (clay), cl (clay loam), fsl (fine sandy loam), l (loam), ls (loamy sand), s (sand), sc (sandy clay), scl (sandy clay loam), sic (silty clay), sicl (silty clay loam), sil (silt loam) and sl (sandy loam). Subscripts indicate the number of soils studied with a given texture.

[2] A, alfalfa (*Medicago sativa* L.); B, barley (*Hordeum vulgare* L.); C, corn (*Zea mays* L.); Cb, coastal bermudagrass (*Cynodon dactylon* L. Pers.); Ce, cereal; Cp, cowpea (*Vigna unguiculata* L.); C_s, silage corn (*Zea mays* L.); Ct, cotton (*Gossypium hirsutum* L.); Gcl, grass-clover; L, ley; P, pea (*Pisum* L.); Pm, pearl millet (*Pennisetum glaucum* L. R. Br.); Po, potato (*Solanum tuberosum* L.); Pr, perennial ryegrass (*Lolium perenne* L.); Rc, root crop; Rcl, red clover (*Trifolium pratense* L.); Ri, rice (*Oryza sativa* L.); Ry, rye (*Secale cereale* L.); S, soybean (*Glycine max* L. Merr.); Sb, sugarbeet (*Beta vulgaris* L.); Sp, sweet potato (*Ipomoea batatas*); W_s, spring wheat (*Triticum aestivum* L.); W_w, winter wheat (*Triticum aestivum* L.). Values in parentheses indicate the number of separate trials summarized.

[3] Parentheses indicate digital uncertainty in estimating data reported in figures.

[4] All crops were grown annually.

[5] Prior to 1901, the cropping system was W_w–W_w (1856–1875) or Po–Po (1876–1901).

[6] Assumed as the depth for sampling surface soil.

[7] Rice grain was assumed to contain 0.04 g K kg^{-1} at a moisture content of 140 g kg^{-1} [79].

[8] Cropped to cereals between 1982 and 1987, with 4 years of barley, 1 year of oats (*Avena sativa* L.) and 1 year of winter wheat.

[9] Includes atmospheric K deposition.

Table 3. Speciation of potassium in surface (0–18 cm) samples collected in August and September between 1986 and 1989 from a Drummer soil under a corn–soybean rotation with no P or K fertilization since 1970.[1]

Year	Exchangeable K[2]	Non-exchangeable K recovered in six successive extractions[3]							Total K[4]
		Ext. 1	Ext. 2	Ext. 3	Ext. 4	Ext. 5	Ext. 6	Ext. 1–6	
		kg ha^{-1}							
1986	240 (16)	1048 (54)	616 (58)	463 (37)	351 (8)	252 (37)	239 (28)	2969	42,271 (682)
1987	244 (18)	932 (47)	588 (43)	407 (35)	435 (16)	351 (16)	308 (24)	3021	ND
1988	224 (23)	1120 (50)	700 (56)	476 (8)	336 (32)	379 (21)	267 (8)	3278	ND
1989	276 (25)	987 (24)	627 (35)	448 (16)	358 (14)	299 (29)	269 (16)	2988	42,208 (680)

[1] 160–180 kg N ha^{-1} applied for corn production in 1986 and 1988. All values reported as a mean of triplicate determinations performed on a sample composited from 45 to 75 cores collected in August and September of each year. Standard deviations shown in parentheses.
[2] Determined by extraction with 1 M $NH_4C_2H_3O_2$ (pH 7)[24] after air drying at 40°C.
[3] Determined after extraction of exchangeable K, by boiling with 1 M HNO_3[24].
[4] Determined by fusion with $LiBO_2 \cdot 8H_2O$, followed by dissolution in 1 M HNO_3[25]. ND, not determined.

Fertilizer value of potassium chloride

Besides being abundant in soils and plant residues, K is notable as the only macronutrient dominated by inorganic forms in both the soil and plant, and thus availability is not dependent upon microbial transformations. Uptake occurs much more readily for K^+ than for Ca^{2+} or Mg^{2+} because of greater membrane permeability further enhanced at low concentrations by active diffusion, while specialized transport systems selective for K rapidly distribute this nutrient in the plant[33,107]. Under these circumstances, and considering the ubiquitous nature of K, it becomes clear why many years can be required to induce fertilizer K response in long-term static plot experiments[59,60,71,77,108] (see also supplemental references [46–52] for the online version of the paper). On the basis of such findings, there is little reason to expect economically viable crop response to shorter periods of K fertilization that limit check-plot depletion, and a far lower likelihood of response in a production setting where the entire field shares the same history of regular fertilizer K inputs.

This view was indeed confirmed by compiling a global database of crop response to KCl from 2121 short-term field trials conducted by public universities or experiment stations. The resulting database is too extensive to be accommodated herein but is available in the online supplement as Table S4 (for the online version of the paper). As hypothesized, KCl fertilization was often ineffective for increasing productivity, according to non-significant responses that occurred in approximately 76% of the total trials surveyed. The inherent capability for plant uptake of soil K is manifestly evident from studies in which shallow-rooted crops growing on sandy soils were non-responsive to K fertilization[109–112], and often made fertilizer K superfluous when deeper rooted crops had access to profile K supplies in more productive soils. Unfortunately, KCl usage in the latter case has long been exacerbated by a buildup-maintenance philosophy that promotes intensive fertilizer K inputs without regard to huge soil K reserves or their recycling through crop residues.

To ascertain the value of K fertilization, those trials showing a statistically significant response to KCl fertilization, accounting for 24% of the total database, are presented herein in Table 4. Most of the responses were positive and occurred on coarse-textured, organic or highly weathered soils inherently low in K-supplying power (231 site-years); when the above-ground residues were removed (191 site-years); with crops having a shallow or low-density rooting system (62 site-years); and/or when subsoil rooting was restricted (12 site-years). In the absence of such factors, there is very little reason to expect a significant yield response to KCl fertilization.

The input-intensive approach to fertilizer K management can have negative economic consequences for producers, which are apt to go unnoticed unless fertilizer response is determined relative to yield in the absence of fertilization. These consequences are to be expected considering the ample evidence in Table S4 (for the online version of the paper) that KCl inputs are often ineffective for increasing yield, but will be more serious when yield is depressed. The latter effect has indeed been observed, and was significant in field studies with corn[38,144,148,192], soybean[120,125,131,175], wheat (*Triticum aestivum* L.)[186], sugarbeet (*Beta vulgaris* L.)[139], sugarcane (*Saccharum officinarum* L.)[127], alfalfa[145], peanut (*Arachis hypogaea* L.)[109,191], rape (*Brassica napus* L.)[176] and cowpea (*Vigna unguiculata* L.)[166]. In several of these studies, the loss of yield was intensified by increasing the rate of KCl application[38,109,120,125,175,192], and in some cases the higher rate transformed significant yield gain to loss[127,186].

Yield reductions due to KCl fertilization, as documented in Table 4, can be explained by the high salt index of this fertilizer, which has been implicated as a detrimental factor for crop germination and growth[193–195] and microbial processes[196,197]. More serious consequences can occur because of the anion supplied by KCl.

Table 4. Significant yield responses to KCl fertilization in field studies documented by a survey of 211 peer-reviewed and university publications involving ≤10 years of KCl application at a fixed rate.[1]

Location	Soil order[2]	Exchangeable K[3]	K applied (as KCl)	Site-years studied[4]	Cropping system[5]	Yield without fertilizer K[6]	Yield response to K[7]		Reference
							Lowest	Highest	
		kg ha^{-1}	kg ha^{-1} yr^{-1}			Mg ha^{-1}	----------%	----------	
North America									
Canada									
Manitoba	Mollisols (scl)	50–310 (15)	0–200	15	A[9]	16.7	59* (50)	174* (200)	113
Ontario	Alfisols (sl)	NR	0–126	4	O–Po	19.8	24* (126)	24* (126)	114
USA									
Alabama	Ultisols (sil)	42	0–150	3	Bg[9]–S	2.6	27* (75)	44* (150)	115
	Ultisols (fsl, sil)	25–42[8](20)	0–112	6	Tf, Wc[9]	3.6	25[ns] (28)	46* (112)	116
Alaska	Inceptisols (sil)	256	0–186	2	Sbg[9]	3.2	−15[ns] (112)	31* (186)	117
Arkansas	Alfisols (sil)	112 (16)	0–75	3	S	2.8	8* (75)	8* (75)	118
	Alfisols (fsl)	213–269 (15)	0–84	6	Ct	2.1	10* (28)	22* (84)	119
	Alfisols (sil)	NR	0–1175	8	S	2.7	−21* (1175)	−9[ns] (587)	120
California	Mollisols (sl)	65[8]	0–480	3	Ct	2.(4)	11** (120)	31*** (480)	121
	Alfisols (l)	67[8] (20)	0–100	3	Ri[9]	7.(8)	5* (63)	7* (100)	122
Colorado	Mollisols (cl)	335[8] (15)	0–750	16	A[9]	52.7	6* (375, 750)	6* (375, 750)	123
Connecticut	Inceptisols (fsl)	121[7]	0–448	6	Rc[9]	10.7	7* (448)	12* (224)	124
Delaware	Ultisols (sil)	207	0–223	20	S	2.0	−30* (223)	−11* (56)	125
Florida	Spodosols (fs)	45–52[8] (15)	0–200	1	S–Vg	4.0	6[ns] (50)	15* (200)	126
	Histosols	43 (30)	0–560	1	Sc[9]	97.2	−4** (560)	6** (280)	127
	Ultisols (lfs)	17–150[8] (15)	0–418	2	C–(S or Ar[9])	9.5	19* (209)	21* (418)	128
Georgia	Ultisols (sl)	NR	0–188	3	Bg[9]	9.5	11* (47)	14* (188)	129
	Ultisols (fs)	30 (15)	0–168	6	Pn	2.3	17* (34)	34* (168)	130
	Ultisols (ls, sl)	41–182	0–224	9	Pn	4.(2)	−4* (224)	−1[ns] (121)	109
	Ultisols (s)	NR	0–186	30	S	1.7	−30* (186)	−30* (186)	131
	Entisols (ls)	10[8] (25)	0–56	3	C–Pn	3.5	47* (56)	47* (56)	132
Idaho	Mollisols (gl)	92–112[8] (20)	0–415	5	A[9]–Po	24.8	20* (415)	21* (208)	133
Illinois	Alfisols (sil)	60–86 (15)	0–224	2	Sg–C	4.1	2[ns] (28)	60** (224)	38
	Alfisols (sil)	63–161 (15)	0–224	2	C	4.9	20** (28)	118** (112)	134
	Inceptisols (sil)	166 (15)	0–112	1	C	8.3	−1[ns] (28)	7* (56)	
Indiana	Alfisols (fs)	51[8] (18)	0–372	3	A[9]	3.7	32** (93)	54** (372)	135
	Alfisols (sil)	74[8] (18)	0–372	2	A[9]	5.1	15* (93)	21* (372)	
Iowa	Mollisols (sl-sil)	141–491 (15)	0–335	9	A[9]	4.3	1[ns] (74, 112)	12* (335)	136
	Alfisols (sil)	62–190 (15)	0–140	5	A[9]–C	5.7	10* (28)	16* (112)	38
Kansas	Alfisols (sil)	45–108[8] (15)	0–140	6	(A[9] or Bt[9])–Sr	6.(0)	10* (70, 140)	10* (70, 140)	137
Kentucky	Ultisols (sil)	NR	0–372	3	Tf/Wc[9]	5.1	0[ns] (372)	7* (140)	138
Michigan	Alfisols (sl, l)	77–242 (15)	0–335	7	A, Rcl, Sbg[9]	4.1	8[ns] (19)	33* (335)	136
	Alfisols (l)	NR	93–186	1	Sb	50.7[10]	−6* (186)	−6* (186)	139
Minnesota	Alfisols (sil)	102–142 (15)	0–140	2	A[9]–C	5.2	10[ns] (28)	25* (140)	38
	Entisols (fs)	122 (15)	0–140	1	A[9]–C	3.9	−18* (140)	3[ns] (28)	
	Histosols	37 (15)	0–140	1	C–C	2.4	38* (140)	46* (84, 112)	
	Mollisols (ls, sil)	111–198 (15)	0–140	2	A[9]–C	4.6	16* (28)	37** (140)	

Mississippi	Entisols (sil)	NR	0–112	2	C–Ct	1.3	17* (37)	31* (112)	140
	Inceptisols (fsl)	289–465 (15)	0–112	8	Ct	1.0	9* (112)	9* (112)	141
	Entisols (si)	115[8] (15)	0–204	2	Ct	1.2	7* (68)	13* (204)	142
	Inceptisols (fsl)	138–159[8] (15)	0–112	11	Ct	1.1	5* (112)	5* (112)	143
Nebraska	$Entisols_1$, $Mollisols_{15}$	91–609[8] (20)	0–40	16	C–S	14.4	−3* (40)	−3* (40)	144
New Mexico	Entisols (fsl)	NR	0–56	3	A[9]	16.6	−2* (56)	−2* (56)	145
North Carolina	Ultisols (fsl)	12[8]	0–112	3	C–S	0.35	131* (11)	342* (112)	146
North Dakota	Mollisols (l)	570–940	0–99	4	B	2.7	1[ns] (24)	4* (99)	147
Ohio	Mollisols (sicl)	NR	0–360	2	C	9.2	−20*** (90)	−19*** (360)	148
	Alfisols (sil)	190	0–74	6	C–S	3.0	1[ns] (37)	7* (74)	149
Pennsylvania	Alfisols (sicl)	32 (15)	0–112	6	Og[9]	4.0	21* (56)	29* (112)	150
	$Alfisols_4$ (sil), $Ultisols_2$ (sil)	61–140 (15)	0–525	16	A[9]	2.(8)	66* (175)	72* (350)	151
South Dakota	Mollisols	> 391	0–71	20	O	2.5	3* (35, 71)	3* (35, 71)	152
Tennessee	Mollisols (fsl)	NR	0–186	1	C	5.0	−2[ns] (149)	18* (19)	153
	Alfisols (sil)	198–444 (15)	56–112	6	Ct	1.8[10]	5* (112)	5* (112)	154
Texas	Ultisols (fs, fsl)	NR	0–278	6	Bg[9]	10.3	24* (139, 278)	24* (139, 278)	155
Utah	Mollisols (sil)	59–77[8] (30)	0–224	2	Po	37.4	15* (224)	15* (224)	156
Virginia	Ultisols (sl)	55 (15)	0–372	6	S	1.8	25* (372)	25* (372)	157
	Ultisols (cl)	66–121	0–112	2	S	1.6	85* (28)	139* (112)	158
Wisconsin	Mollisols (sil)	142 (15)	0–1120	3	A[9]	6.5	22* (56)	53* (672)	159
	Alfisols (sil)	124 (15)	0–1792	2	A[9]	8.3	11[ns] (1344)	32* (448)	160
	Mollisols (sil)	167 (15)	0–896	1	A[9]	6.2	14* (896)	22* (448)	161
	Mollisols (sil)	142 (15)	0–672	2	A[9]	5.8	34* (224)	37* (672)	162
	Entisols (ls)	72–90[8]	0–372	4	Po	34.8	17* (93)	25* (280)	163
South America									
Brazil	Oxisols	46[8]	0–168	9	Ri–Ri	1.1	9* (42)	19** (126)	164
	Oxisols (ls)	20–52[8] (20)	0–199	2	S	1.(5)	65* (33)	111* (133)	165
Peru	Ultisols	55[8] (15)	0–120	6	Ri–Cp[9]	2.1	4[ns] (20)	22* (80)	166
		55[8] (15)	0–120	4	Ri–Cp[9]	0.8	−24* (20)	25* (120)	
Venezuela	Oxisols (scl)	38[8]	0–135	2	S	1.0	8[ns] (9)	173* (108)	167
Europe									
Macedonia	Entisols	83[8] (20)	0–100	2	Po	33.3	13** (100)	13** (100)	168
Africa									
Madagascar	Oxisols (sl)	55[8] (20)	0–75	5	S	0.5	278** (25)	422** (50, 75)	169
Nigeria	Oxisols (ls-sl)	31–817[8] (15)	0–75	9	Ct	1.9	35* (25)	42* (75)	170
	Alfisols, Ultisols (ls)	39–78[8] (15)	0–40	20	Gn	1.4	24* (20)	31* (40)	171
	Inceptisols (ls)	20–66[8] (15)	0–40	20	Gn	1.1	20* (20)	22* (40)	
Asia									
Bangladesh	Inceptisols (scl)	20[8]	28–37	1	Sa	1.3[10]	8* (37)	8* (37)	172
	Entisols (scl)	78–86[8] (30)	0–180	2	Sc[9]	74.8	6* (45, 135)	9* (70, 90)	173
	Inceptisols (sicl)	133[8] (20)	66–133	1	Ra[9]	24.0[10]	8* (100)	12* (133)	174
India	Vertisols	NR	9–150	2	S	3.1[10]	−7* (37)	−3* (19)	175
	Inceptisols (sl)	223	0–33	1	R[9]	1.1	−20* (33)	−20* (33)	176
	Alfisols, Inceptisols	22–60[8] (15)	0–156	6	W_w[9]	4.(8)	3[ns] (156)	6** (104)	177
	Inceptisols (s-sl)	56–158[8]	0–84	28	Po[9]	12.1	15* (42)	22* (84)	178
	Inceptisols (ls, sil)	NR	0–66	4	Ri[9]	5.3	6* (33)	11* (66)	179
				4	W_w[9]	3.0	12* (33)	24* (66)	

Table 4. (*Cont.*)

Location	Soil order[2]	Exchangeable K[3]	K applied (as KCl)	Site-years studied[4]	Cropping system[5]	Yield without fertilizer K[6]	Yield response to K[7]		Reference
							Lowest	Highest	
	Alfisols (sl)	125	0–156	3	Sc[9]	103.6	11* (125)	19* (188)	180
	Aridisols (sl)	160 (15)	0–75	3	W_w[9]	4.7	10* (50)	14* (75)	181
	Inceptisols (sl)	138	0–166	4	Po[9]	28.4	17* (42)	38* (166)	182
	Inceptisols (sl)	75[8]	62–187	8	Po[9]	21.3[10]	17* (124)	21* (187)	183
Indonesia	Oxisols	51[8]	0–75	1	C	0.5	400* (25)	600* (75)	184
	Oxisols	NR	0–105	1	P	0.2	1[ns] (26)	11* (105)	185
	Ultisols (c)	55[8] (12)	23–83	6	Cp–Ri–S[9]	6.3[10]	37* (83)	37* (83)	105
Pakistan	Aridisols (cl)	135[8] (15)	0–148	1	Ri–W_w[9]	2.5	−14[ns] (111)	23* (37)	186
		160[8] (15)	0–148	1	F–W_w[9]	2.1	−12* (148)	16* (37)	
	Aridisols (sicl)	125[8] (25)	0–199	1	W_w[9]	3.6	11[ns] (33)	29** (133–199)	187
Turkey	Vertisols (c)	560–750[8]	0–199	2	Ct	2.6	12* (66)	27* (133)	188
Vietnam	Ultisols	8[8] (20)	0–133	9	Cs	2.8	454* (33)	546* (133)	189
Australasia									
Australia	$Alfisols_4$, $Entisols_5$, $Inceptisols_1$ (s)	19–37[8] (10)	0–60	10	Cn	1.(2)	25* (15)	51* (60)	190
Mauke	Ultisols (cl)	NR	0–132	1	Pn	1.2	−16* (132)	−16* (132)	191

*,**,***Significant at $\alpha = 0.05$, 0.01 and 0.001, respectively; ns, not significant.

[1] A complete listing of all studies surveyed can be found in Table S4, for the online version of the paper.

[2] Surface texture designated parenthetically as c (clay), cl (clay loam), fs (fine sand), fsl (fine sandy loam), gl (gravelly loam), l (loam), lfs (loamy fine sand), ls (loamy sand), s (sand), scl (sandy clay loam), si (silt), sicl (silty clay loam), sil (silt loam) and sl (sandy loam). Subscripted values indicate the number of soils studied that represent a specific order.

[3] Air-dried data reported. Values in parentheses indicate sampling depth in cm. NR, not reported.

[4] Values take into account the number of genotypes studied and/or the use of multiple tillage systems.

[5] A, alfalfa (*Medicago sativa* L.); B, barley (*Hordeum vulgare* L.); Bg, bermudagrass (*Cynodon dactylon* L. Pers.); Bt, birdsfoot trefoil (*Lotus corniculatus* L.); C, corn (*Zea mays* L.); Cn, canola (*Brassica napus* and *campestris*); Cp, cowpea (*Vigna unguiculata* L.); Cs, cassava (*Manihot esculenta*); Ct, cotton (*Gossypium hirsutum* L.); F, fallow; Gn, groundnut (*Arachis hypogoea* L.); O, oat (*Avena sativa* L.); Og, orchardgrass (*Dactylis glomerata* L.); P, pea (*Pisum sativum* L.): Pn, peanut (*Arachis hypogaea* L.); Po, potato (*Solanum tuberosum* L.); R, rape (*Brassica napus* L.); Ra, radish (*Raphanus sativus* L.); Rc, reed canarygrass (*Phalaris arundinacea* L.); Rcl, red clover (*Trifolium pratense* L.); Ri, rice (*Oryza sativa* L.); S, soybean (*Glycine max* L. Merr.); Sa, safflower (*Carthamus tinctorius* L.); Sb, sugarbeet (*Beta vulgaris* L.); Sbg, smooth bromegrass (*Bromus inermis* Leyss.); Sc, sugarcane (*Saccharum officinarum* L.); Sg, small grain; Tf, tall fescue (*Festuca arundinacea* Schreb.); Vg, vegetables; Wc, white clover (*Trifolium repens* L).; W_w, winter wheat (*Triticum aestivum* L.). Underscoring indicates the crop(s) studied for K response.

[6] Data for legumes were obtained from fertilization with P but not K, whereas data for non-legumes were obtained from fertilization with N or N and P but not K. Parentheses indicate digital uncertainty in estimating data reported in figures. When otherwise reported, grain yields were adjusted to market-standard moisture content.

[7] Estimated as 100 × (fertilized yield − unfertilized yield)/unfertilized yield. Values in parentheses indicate the rate of K application in $kg\,ha^{-1}\,yr^{-1}$. Application of N or N and P was constant throughout the range of K rates cited.

[8] Values expressed as $mg\,kg^{-1}$.

[9] Above-ground residues removed.

[10] Yield when the lowest K rate was applied with N or N and P.

Many leguminous crops are sensitive to Cl^- toxicity, including soybean[120,131] and alfalfa[159,160,198], and Cl^- can reduce soil N availability by inhibiting nitrification in soils[195,196,199,200] (see also supplementary references [53–55] for the online version of the paper) and by acting as a competitive anion that suppresses plant uptake of NO_3^- [147,201,202] (see also supplementary references [38] and [56–59] for the online version of the paper). A further difficulty arises from the mobility of Cl^- in soils, which intensifies profile leaching of Ca^{2+} as a counterion[203–205].

Producers have long been led to believe that KCl fertilization serves an essential role, not only for sustaining crop yield but more importantly, for ensuring a high-quality product that will maximize economic return. To ascertain the credibility of the latter claim, a thorough survey was undertaken of peer-reviewed and university publications that provide the most reliable source of information regarding the agronomic effects of KCl. The findings, summarized in Table 5 for more than 1000 field experiments, altogether contradict the prevailing belief in the value of this fertilizer for improving crop quality, since the frequency of positive responses was only about 8%. On the contrary, the qualitative effect of KCl was negative in 57% of the trials surveyed. In some of these trials, crop quality was reduced despite a significant yield increase[159,160].

One of the better known consequences of KCl fertilization, reported in Table 5 for studies with corn[153,201,212,216], wheat[221] and sorghum (*Sorghum bicolor* L. Moench)[137], arises from the antagonistic effect of Cl^- on NO_3^- uptake that reduces lodging or stalk rot when susceptible cereal varieties are grown on a soil with high N-supplying power and/or with heavy inputs of fertilizer N, but at the expense of promoting NO_3^- loss through leaching or denitrification. The use of KCl can also have a beneficial effect by increasing the fiber strength (micronaire) of cotton (*Gossypium hirsutum* L.) grown on soils inherently limited in K reserves[222–224,226], which would be expected considering the lack of a dense rooting system or residue K inputs.

Other qualitative benefits are often claimed for KCl fertilization of grain, fiber, oilseed or sugar crops, but these are difficult to reconcile with the listings in Table 5. This fertilizer, for example, has usually been ineffective for reducing disease severity in barley (*Hordeum vulgare* L.), wheat, soybean or cotton, and even with a positive effect, there was no significant yield increase[202,210,219,225] except where root rot was associated with a high content of NO_3^- but not K^+ or Cl^-[147] or when a susceptible variety was grown on an infertile sand[207]. There was likewise little evidence that KCl enhances sucrose content in sugar crops or oil, protein or fiber content or composition. Instead, these constituents were more likely to be adversely affected, as reported by Fintel and Quicke[214] for corn protein that declined in niacin and tryptophan. Such a decline has serious implications for human nutrition in the developing world, where grain is the staple food source.

Tuber crops are no less important to human nutrition, and particularly potato (*Solanum tuberosum* L.) that has a much higher K requirement than grain crops. In many parts of the world, KCl fertilization is a normal practice for potato production; however, there is a hidden cost from lowering starch content, which in turn reduces specific gravity. These effects, clearly documented in Table 5, have adverse consequences for human health such as obesity and cardiovascular disease, arising from greater oil retention in processed products such as potato chips and french fries. The anion supplied by KCl intensifies the decline in starch or dry matter content and specific gravity[163,238,241–244], and becomes a toxicological concern by enhancing the mobility and plant uptake of soil Cd[239,240,247]. The latter problem has also been reported for cereal crops[208,220], and may thus be of broader interest for contamination of the food chain, particularly in view of recent clinical evidence linking breast cancer to dietary Cd exposure[248].

Forage crops remove large amounts of K because their aboveground biomass is repeatedly harvested, and intensive usage of fertilizer KCl is widely promoted to not only sustain productivity, but more importantly, to ensure high forage quality that is critical to animal nutrition. Unfortunately, Table 5 provides no evidence that KCl is of any qualitative benefit to forage crops; rather, the effect was invariably negative, often involving a low content of Ca and/or Mg[159–161,229,230] that predisposes livestock to milk fever[249,250] or grass tetany[229,251]. To prevent these disorders while improving forage quality, Cherney et al.[252] have recommended that the use of fertilizer K or manure be avoided on dairy farms in the northern USA, unless K deficiency is detected by plant analysis.

Elevated K supplies have long been recognized to have an antagonistic impact on the bioavailability of Ca and Mg, with adverse consequences for crop yield and quality. For example, McCalla[253] found that raising the K:Ca ratio in culture studies led to a progressive decrease in the growth of legume bacteria and in the nodulation of alfalfa and soybean roots. This imbalance would normally be ameliorated by liming, but even a neutral Ca salt can be utilized successfully to enhance soybean nodulation on an acidic soil[254]. There are broader ramifications from the antagonistic effect of K on the Ca content of food crops, because low dietary Ca intake has been linked to several human diseases, including osteoporosis, rickets and colon cancer[255–259].

The problems associated with KCl usage have been thoroughly documented for arid and semi-arid regions by Krauss and Saurat[260], and arise in part from the presence of a bioactive anion that has detrimental consequences for crop yield and quality. Some of these consequences can be avoided by applying K_2SO_4 instead of KCl. The benefits of this strategy for increasing crop yield and/or quality have been documented in numerous studies with potato[133,163,168,261–265] and to a lesser extent

Table 5. Condensed version of a survey of peer-reviewed and university publications concerning the effect of KCl fertilization on the quality of selected food, feed and fiber crops.[1]

Crop(s)[2]	Study location(s)	Study period[3]	Site-years studied[4]	Soil type[5]	Parameter of K response	Net effect on crop quality	Reference
Grain crops							
Barley	Alberta	1989–1998	115	NR	Root rot infestation	None	206
	Australia	2003	1	s	Powdery mildew severity	Positive	207
	Manitoba	1990–1992	6	fsl, cl	Cd content	Negative	208
	North Dakota	1964–1967	13	sl-sicl	Grain protein content	None	209
		1983	5	l	Root rot induced by high N	Positive	202
		1984	6	l	Root rot induced by high N	Positive	147
Barley, wheat	Saskatchewan	1987–1989	14	l-c	Root rot	Positive	210
Corn	Illinois	1985–1986	10	sil	Leaf Ca and Mg content	Negative	211
	New Jersey	1994–1995	2	sl	Stalk rot induced by high N	Positive	212
	New York	1956	1	NR	Stalk rot induced by high N	Positive	201
	North Carolina	1982–1983	10	ls	Ca and Mg content	Negative	213
	South Africa	1957–1959	1	NR	Niacin and tryptophan content	Negative	214
	Tennessee	1951	1	fsl	Lodging induced by high N	Positive	153
		1957	10	l	Ca and Mg content	Negative	215
	Wisconsin	1962	1	sil	Lodging induced by high N	Positive	216
Oat	South Dakota	1986–1987	15	NR	Crown rust incidence	None	152
					Lodging	Variable	
Sorghum	Kansas	1995–1996	4	sil	Lodging induced by high N	Positive	137
Soybean	Delaware	1974–1975	40	ls, sil	Gray seed mold, purple seed stain	None	125
	Georgia	1981	30	s	Cl^- toxicity	Negative	131
	Iowa	1995–2001	25	l-cl	Seed oil and protein content	None	217
	North Carolina	1943	3	fsl	Seed protein content	Negative	146
	Virginia	1974–1975	2	cl	Nodulation	Positive	158
	Wisconsin	1927	1	sl	Nodulation	Negative	218
Wheat	Nepal	2000–2002	4	l	Spot blotch severity	Positive	219
	North Dakota	1997	124	NR	Cd content	Negative	220
	Pakistan	1980–1981	3	cl	Grain content of crude protein	Positive	186
	Pakistan	1956–1957	5	NR	Lodging induced by high N	Positive	221
Fiber crops							
Cotton	Alabama	1960–1961	2	sl	Micronaire	Positive	222
	Brazil	2001–2003	3	cl	Micronaire	Positive	223
	California	1985–1987	4	sl	Micronaire	Positive	224
	Mississippi	1986–1988	3	fsl	Verticillium wilt severity, nematode infestation	Positive	225
					Micronaire	None	
		1991–1992	16	fsl	Micronaire	Positive	226
		1993–1994	8	fsl	Lint percentage	Positive	141
		1995–1997	11	fsl	Micronaire	None	143
		1999–2001	27	fsl	Nematode infestation	Negative	227
	Turkey	1999–2000	2	c	Micronaire	None	188

Forage crops							
Alfalfa	Wisconsin	1970–1972	3	sil	Ca and Mg content	Negative	159
		1970–1972	3	sil	Cl^- toxicity	Negative	198
		1972–1973	2	sil	Ca and Mg content	Negative	160
		1998–2001	11	ls-sil	Ca and Mg content	Negative	228
Mixed grass-clover	Australia	1966–1971	4	NR	Incidence of grass tetany	Negative	229
Red clover	Wisconsin	1974	1	sil	Ca and Mg content	Negative	161
Sorghum × sudangrass	New York	2002–2003	2	sil	Ca and Mg and crude protein content, milk production	Negative	230
Subterranean clover-ryegrass	Australia	1968 1973	27	s-l	Mg content	Negative	231
Tall fescue	West Virginia	1971–1975	32	sicl	Ca and Mg content	Negative	232
Oilseed crops							
Peanut	Alabama	1973–1986	39	ls-sl	Kernel grade	None	110
Rape	Australia	1993–2003	53	ps	Seed oil content	None	233
	India	1969–1970	1	sl	Seed protein and oil content	Negative	176
Safflower	Bangladesh	1973 1974	1	scl	Seed protein content	Negative	172
					Seed oil content	Positive	
Sunflower	Minnesota, North Dakota	NR	22	fsl-sic	Cd content	Negative	234
Sugar crops							
Sugarbeet	England	1959- 1962	42	NR	Sucrose content, juice purity	None	235
Sugarcane	Brazil	2006	1	scl	Sucrose content	None	236
	Florida	1970–1972	2	m	Sucrose content	None	237
		1978	1	m	Sucrose content	Negative	127
	India	1989–1992	3	sl	Sucrose yield	Positive	180
Tuber crops							
Potato	Australia	1982–1984	30	NR	Specific gravity	Negative	238
		1992–1993	6	sl-c	Cd content	Negative	239
		1991–1992	5	s-l	Cd content	Negative	240
		1989–1999	33	s-c	Dry matter content	Negative	241
	Idaho	1970–1976	4	ls	Specific gravity	Negative	242
		NR	4	gl	Specific gravity	Negative	133
	India	2001–2002	4	sl	Dry matter content, specific gravity, chip color	Negative	182
		2000–2001	4	sl	Tuber weight	Positive	183
	Ireland	1961–1966	27	NR	Dry matter content	Negative	243
	Macedonia	1995–1996	2	NR	Starch content	None	168
	Maine	1955–1958	56	NR	Specific gravity	Negative	244
	Sweden	1964–1967	68	sl-l	Dry matter content	Negative	245
	Utah	1988–1989	2	sil	Specific gravity	Negative	156
	Wisconsin	1992–1995	11	ls-sil	Specific gravity	Negative	163
Sweet potato	Louisiana	1968–1975	13	sil	Dry matter and protein content, firmness	Negative	246

[1] A complete listing of all studies surveyed can be found in Table S5 for the online version of the paper.
[2] Latin names for crops not included in Table 4: ryegrass, *Lolium perenne* L. and *Lolium rigidum* Gaudin; subterranean clover, *Trifolium subterranean* L.
[3] NR, not reported.
[4] Values take into account number of genotypes studied.
[5] Abbreviations: c (clay), cl (clay loam), fs (fine sand), fsl (fine sandy loam), gl (gravelly loam), l (loam), lfs (loamy fine sand), ls (loamy sand), m (muck), p (peat), ps (predominately sandy), s (sand), scl (sandy clay loam), sic (silty clay), sicl (silty clay loam), sil (silt loam), sl (sandy loam). NR, not reported.

with several other crops, including alfalfa[160], soybean[266] and wheat[186,267].

Tables 4 and 5 (see also Tables S4 and S5 for the online version of the paper) provide little agronomic justification for the buildup-maintenance philosophy that for several decades has intensified the input of fertilizer K, often in conjunction with direct or indirect subsidies at considerable public expense[268,269] (see also supplemental references [60–62] for the online version of the paper). The result has been massive KCl consumption, which for Illinois has surpassed 21 Tg since 1950, equivalent on average to approximately 2200 kg ha^{-1} [270–272]. A cumulative effect on soil physical and chemical properties would be expected, since K is prone to interlayer fixation that collapses 2:1 clay minerals and converts an active, swelling smectite to an inactive, non-swelling illite[26,273]. The stabilizing value of KCl has long been recognized in the construction of impervious pavement and foundations[274–277]. Unfortunately, the agronomic consequences include a loss of CEC[71,77,278–280] and lower water-holding capacity, which is not conducive to crop growth and productivity.

Conclusions

Since the onset of industrialized agriculture more than half a century ago, the view has been inculcated that intensive inputs of fertilizer K are indispensible for maximizing crop yield and quality and for the long-term maintenance of soil productivity. This view cannot be reconciled with the considerable volume of scientific evidence presented herein, encompassing soil testing for plant-available K and the consequences of KCl fertilization for agricultural productivity, food safety and soil degradation.

If fertilizer K usage is to be profitable in a production setting, current recommendations will no longer suffice that rely on soil testing for exchangeable K. As a more viable alternative, producers should periodically carry out their own strip trials, for comparing yield with and without upward and downward K rate adjustment. Initially, a 3-year period would be appropriate for repeating these trials, but a longer interval could safely be employed with cash-grain cropping that limits K removal. To avoid the adverse consequences of Cl^-, K_2SO_4 would be preferred as a fertilizer source.

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Biogas in organic agriculture—effects on productivity, energy self-sufficiency and greenhouse gas emissions

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Abstract

Anaerobic digestion of manure and crops provides the possibility of a combined production of renewable energy and organic fertilizer on organic farms and has been suggested as an option to improve sustainability of organic agriculture. In the present study, the consequences of implementation of anaerobic digestion and biogas production were analyzed on a 1000 ha model farm with combined dairy and cash crop production, representing organic agriculture in Denmark. The effects on crop rotation, nitrogen flows and losses, yield, energy balance and greenhouse gas (GHG) emissions were evaluated for four scenarios of biogas production on the farm. Animal manure was digested for biogas production in all scenarios and was supplemented with: (1) 100 ha grass–clover for biogas, (2) 100 ha maize for biogas, (3) 200 ha grass–clover for biogas and reduced number of livestock, and (4) 200 ha grass–clover for biogas, reduced number of livestock and import of biomass from cuttings made in ungrazed meadows. These four scenarios were compared with the current situation in organic agriculture in Denmark and to a situation where slurry from conventional agriculture is no longer imported. Implementation of anaerobic digestion changed the nitrogen flows on the farm by increasing the slurry nitrogen plant availability and introducing new nitrogen sources from legume-based energy crops or meadows. The amount of nitrogen available for application as fertilizer on the farm increased when grass–clover was used for biogas production, but decreased when maize was used. Since part of the area was used for biogas production, the total output of foodstuffs from the farm was decreased. Effects on GHG emissions and net energy production were assessed by use of the whole-farm model FarmGHG. A positive farm energy balance was obtained for all biogas scenarios, showing that biomass production for biogas on 10% of the farm area results in an energy surplus, provided that the heat from the electricity production is utilized. The energy surplus implies a displacement of fossil fuels and thereby reduced CO_2 emission from the farm. Emissions of N_2O were not affected substantially by biogas production. Total emissions of methane (CH_4) were slightly decreased due to a 17–48% decrease in emissions from the manure store. Net GHG emission was reduced by 35–85% compared with the current situation in organic agriculture. It was concluded that production of biogas on organic farms holds the possibility for the farms to achieve a positive energy balance, provide self-sufficiency with organic fertilizer nitrogen, and reduce GHG emissions.

Key words: biogas, anaerobic digestion, organic farming, greenhouse gas emissions, net energy yield, farming system

Introduction

Increased public awareness of the need for actions against global warming has brought greenhouse gas (GHG) emissions and the use of fossil energy into focus in agricultural organizations in general and organic agriculture in particular[1]. The reduction of external inputs to the farm through efficient management of materials and energy is part of the organic principles established by the International Federation of Organic Agriculture Movements (IFOAM)[2]. Also in the regulation of organic agriculture in Europe, it is stated that organic farming should be based on 'a minimisation of the use of non-renewable resources' [Council Regulation (EC) No. 834/2007]. Reduction in the dependency on fossil fuels has been identified as one of the important areas for development of organic farming in Denmark[3]. Another important issue is the nitrogen (N) supply that is currently provided in part by the import of animal manure from conventional farms and partly by the use of N-fixing crops

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as green manure. The Danish organic farmers association has planned to phase out use of animal manure from conventional farms by 2021, in order to make organic agriculture independent of conventional farming systems[4].

In 2010, the total area grown organically in Denmark was 173,513 ha, corresponding to 6.6% of the agricultural land[5]. In Denmark, the trade of organic products was doubled between 2005 and 2008, and was until 2011 still increasing by approximately 5% (by value) per year[6]. A further increased conversion of land is necessary if Danish products are to contribute to a continued growth in the organic sector[3], and a doubling of the current organic farm area is planned, together with a significant increase in the production of biogas[7]. At the same time there is a need for improvement of the production system to meet the energy and climate challenge described above, without compromising other organic principles.

Fossil energy use is generally lower in organic than in conventional agriculture. A 41–65% reduction in energy use per hectare for production of winter wheat[8] and a 30–35% reduction for production of spring-sown cereals have been reported[9]. When energy use efficiencies (energy use per unit produce) are compared, the difference is smaller and numbers from 33% less to 21% higher energy use for grain production have been reported[8–10]. When yields in organic farming are substantially lower than in conventional farming, energy efficiencies drop and approach, or even surpass, those of conventional farming. For fodder crops such as grass–clover, with high mineral fertilizer application rates in the conventional system and relatively high yields in both systems, the energy efficiency is, however, up to 90% higher in the organic than in the conventional system[8,10].

Halberg et al.[11] explored options for energy self-sufficiency on organic farms and compared energy production from grass–clover-based biogas to energy production from rapeseed. The biogas scenario was superior to rapeseed on energy balance and furthermore reduced both GHG emission and N leaching. Anaerobic digestion of grass–clover cuttings also provides the possibility for production of organic fertilizer on stockless organic farms, when the digestate (residual product from anaerobic digestion) is recycled to the field[12]. This decreased dependency on animal manure as a fertilizer might provide the possibility of expanding the area of organic cash crop production[13]. When compared with a traditional system, where grass–clover is used as green manure, use of digestate as a fertilizer provides a more even allocation of nutrients in the crop rotation, a better matching of N demand and supply, and thereby higher yields[12]. Furthermore anaerobic digestion of slurry on livestock farms has the potential of reducing the emissions of methane (CH_4).[14]

It has been suggested that a supplement of nutrients in organic farming could be achieved by use of biomass from extensively managed or non-used grasslands. This would in addition contribute to the maintenance of meadows and permanent grasslands, where cutting is essential in order to remove nutrients and maintain biodiversity[15].

The implementation of biogas production on organic farms and its effects depend on the existing farming system and how the implementation changes the farming system. Therefore the aim of this study was to analyze (1) how biogas production in organic farming may be achieved through changes in the crop rotation, and (2) how different scenarios for biogas production affect productivity, N flows, energy balance and GHG emissions of the farm.

Methods

The study applied four steps: (1) establishment of a 1000 ha organic farm model representing organic agriculture in Denmark (reference scenario), (2) creation of scenarios for biogas production on the farm, and (3) analysis of environmental impacts focusing on N flows, crop yields, net energy production and GHG emissions. An updated version of the whole-farm model FarmGHG[16,17] was used for the analysis. FarmGHG is a tool designed for quantification of carbon (C) and N budgets in dairy farm systems and for quantification of direct and indirect gaseous emissions from dairy farms (see section 'Environmental impacts').

Establishment of a 1000 ha organic farm model

Land use. The establishment of a representative 1000 ha organic farm was based on analysis of datasets from the National Danish Agricultural Register. This register contains information on land use in Danish agriculture and, for organic farmers, information on the number of livestock on the farm. The information is derived from EU Single Payment applications of Danish farmers, which are collected in a digital database where all farmers are obliged to declare crop type areas and livestock numbers in order to receive subsidies. These data were combined with data on fertilizer accounts from the Danish Plant Directorate and with soil types as described by Dalgaard et al.[18]. From both registers data from 2006 were used. The combined datasets of 2622 farmers having solely organically farmed areas in their application were divided into groups depending on working hours, livestock and soil type, following Kristensen and Kristensen[19]. Full-time dairy farms and full-time cash crop farms on sandy soils (soils containing less than 15% clay and less than 30% silt) were chosen for further analysis. These two farm types represent 30% of organic farms in Denmark, but manage 61% of the organically certified land. Data on land use, number of livestock and use of manure were averaged for comparative analysis (Figs 1a and 1b, Table 1). Woodland and minor crops representing less

Table 1. Average area and number of livestock on organic cash crop farms and dairy farms on sandy soil in Denmark.

	Cash crop farm	Dairy farm	Combined farm
Agricultural area (ha)	88.5	137.1	1000
Number of cows	0	100	496
Number of heifers	4[1]	108	536
Number of farms in sample	325	455	

[1] Heifers on cash crop farms are not scaled up to the combined farm.

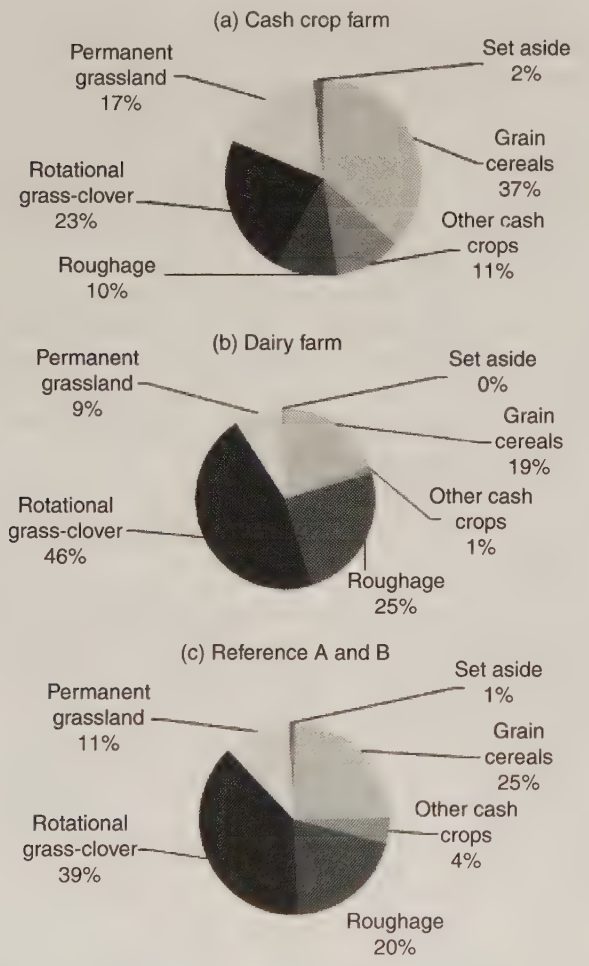

Figure 1. Land use on (a) Danish cash crop farms on sandy soil and (b) Danish dairy farms on sandy soil. (c) The area use of dairy farms and cash crop farms is combined to establish a 1000 ha farm model used as reference scenarios (References A and B).

than 1% of the area on both farm types, and livestock species other than dairy cows and heifers were not included. The two farm types were combined according to the actual distribution of organic dairy farms and cash crop farms on sandy soil; 32% of the area was managed as cash crop farms and 68% of the area was managed as dairy farms (Fig. 1c, Table 1). The average import of slurry from conventional farmers corresponded to 26 kg N ha^{-1} yr^{-1}. The combined farm formed two reference scenarios used for the further analysis: Reference A represented the current situation in Danish organic agriculture with import of manure in slurry from conventional farms, and Reference B represented a situation without import of conventional slurry.

Table 2. Livestock numbers, milk yield and feed plans for cows and heifers.

	Cows	Heifers
Livestock		
Number (RA + B, S1, S2)	496	536
Number (S3, S4)	236	255
Milk yield (kg cow^{-1} yr^{-1})	7969	–
Feed requirement (SFU $head^{-1}$ yr^{-1})*	6181	1536
Feed plan, summer		
Grazing, grass–clover (%)	36	58
Grazing, permanent grass pasture (%)	0	42
Silage, grass–clover (%)	28	0
Other roughage (%)	17	0
Concentrate (%)	19	0
Protein content, summer (%)	16	21
Feed plan, winter		
Silage, grass–clover (%)	64	3
Other roughage (%)	18	97
Concentrate (%)	18	0
Protein content, winter (%)	16	10

* 1 SFU corresponds to 12 MJ metabolizable energy (equivalent to 1 kg of barley).

Livestock. Milk yield followed the Danish annual farm account statistics for 2006[20]. The feed requirement was calculated for cows and heifers according to Olesen et al.[17]. A feed plan was developed (Table 2) based on the crop distribution. It was assumed that the 1000 ha combined farm was self-sufficient with grass–clover and roughage. Feed import was reduced to a minimum and consisted exclusively of barley grain. Usually organic dairy farms import concentrate with a higher protein content than cereal grain[21], but high amounts of protein in the grass–clover compensated for this and the protein content in the diet for the dairy cows followed Danish standards[22].

The National Danish Agricultural Register does not contain information on whether the grass–clover area is used for grazing, silage or other purposes, e.g., green manure. Therefore, the area used for grazing and silage was estimated from the need for roughage, and the remaining area was used for green manure. Organic cattle must have access to grazing from April 15 to November 1, whenever weather and the physical condition of the cattle allow[23]. Based on data from the Danish Agricultural Advisory Service (DAAS)[21] it was assumed that the dairy cows were grazing 8 h per day and heifers were grazing 24 h per day in 184 days out of the 199-day

Table 3. Fertilizer norms[24] and distribution of manure in Reference scenario A.

Crop	Fertilizer norm ($kg N ha^{-1} yr^{-1}$)	Effect of pre crop ($kg N ha^{-1} yr^{-1}$)	Applied total N ($kg ha^{-1} yr^{-1}$)	Applied NH_4-N ($kg N ha^{-1} yr^{-1}$)
Cash crops				
Spring barley	126		105	58
Spring wheat	125	102	19	11
Oats	107	102	4	2
Winter wheat, triticale	166		180	76
Winter rye	121		131	56
Pulse	0		0	0
Potatoes	153	102	39	23
Other cash crops	135	102	28	15
Roughage				
Pulses	0		0	0
Maize	150	102	37	22
Other whole crops	112		122	51
Grass–clover, silage	231		193	106
Grass–clover, grazing	63		53	29
Permanent grass pasture	68		57	31

potential grazing season. In the grazing season, it was assumed that the cows consumed 7 Scandinavian feed unit (SFU) per day from grazing. 1 SFU corresponds to 12 MJ metabolizable energy (equivalent to 1 kg of barley). The heifers covered 100% of their feed requirement from grazing in the grazing season.

Manure. The N demand of the crops was determined using the Danish fertilizer norms for each crop[24] (Table 3). The fertilizer norm is currently set to 85% of the gross margin based, farm economical optimum of plant available N for each crop. If the previous crop is an N-fixing crop, it contributes to plant-available N and reduces the fertilizer norm. Therefore, it was necessary to define a simplified crop rotation. It was assumed that grass–clover fields were rotated every second year. Grass–clover was followed by spring wheat, oats, maize and potatoes. The manure available was insufficient to fulfill the N norm. Therefore, the N application was reduced equally for all crops. NH_4-N applied corresponded to 46% of the N norm (Table 3). Crop yields followed the DAAS estimates for organic crops on sandy soil[25] (Table 4). Maize yield and N application were unchanged when maize was grown for bioenergy. However, N application for grass–clover as an energy crop was reduced to the same level as for grass–clover used for grazing. This was based on the assumption that grass–clover as an energy crop has a lower priority than grass–clover for roughage. The grass–clover yield was adjusted to the lower N application assuming a N response on 13 kg dm $kg N^{-1}$ as reported by Søegaard[26].

Table 4. Organic crop yields on sandy soil[25].

Crop	Yield ($kg dm ha^{-1} yr^{-1}$)
Cash crops	
Spring barley	2975
Spring wheat	2975
Oats	3400
Winter wheat, triticale	3825
Winter rye	3655
Pulses	2180
Potatoes	4800
Other cash crops	900
Roughage	
Pulses	4819
Silage maize	7647
Other whole crops	5441
Grass–clover, silage	8395
Grass–clover, grazing	6044
Permanent grass pasture	1744
Energy crop	
Grass–clover	7395
Silage maize	7647
Meadows for cutting	1853

Scenarios

The overall aim for implementation of biogas production on organic farms in our study was to achieve self-sufficiency with organic fertilizer and energy. Four scenarios for implementation of biogas production were created in order to cover possible implications of biogas production on organic farms: (S1) use of grass–clover or (S2) maize silage as an energy crop, (S3) extension of the cash crop area, and (S4) withdrawal of biomass from unmanaged meadows through cutting and baling.

In S1 and S2, 100 ha were used for production of energy crops (grass–clover and maize silage) for anaerobic digestion (Table 5). In both scenarios, the area for feed production and the number of livestock were sustained.

Table 5. Land use (ha) in References (A + B) and the scenarios for biogas production (S1–S4).

	Ref. A + B	S1: Grass–clover	S2: Maize	S3: Cash crops	S4: Meadows
Cash crops					
Spring barley	79	66	66	132	132
Spring wheat	37	31	31	62	62
Oats	75	63	63	126	126
Winter wheat, triticale	37	31	31	62	62
Winter rye	18	15	15	30	30
Pulses	16	13	13	26	26
Potatoes	7	6	6	12	12
Other cash crops	21	18	18	36	36
Roughage					
Pulses	41	41	41	20	20
Silage maize	53	53	53	25	25
Other whole crops	107	107	107	51	51
Grass–clover, silage	191	191	191	91	91
Grass–clover, grazing	145	145	145	69	69
Grass–clover, green manure	51	0	0	0	0
Permanent grass pasture	113	113	113	54	54
Set-aside grassland (not harvested)	9	7	7	4	4
Energy crop					
Grass–clover	0	100	0	200	200
Silage maize	0	0	100	0	0
Meadows for cutting	0	0	0	0	200
Total	1000	1000	1000	1000	1000 + 200

The 100 ha energy crop was obtained by omitting the grass–clover for green manure and reducing the cash crop area. In S3 and S4, the cash crop area was doubled and 200 ha were used for production of grass–clover for biogas. As a consequence, the area with grass–clover for green manure was omitted and the area for roughage was reduced. The number of livestock on the 1000 ha was reduced proportionally to the decline in roughage area. In S4, an additional 200 ha of extensive meadow (outside of the 1000 ha farm) was harvested and used for biogas production. In all scenarios, the slurry from the livestock excreted in-house was used for biogas production together with the energy crop. The digestate was used as a fertilizer, and the import of manure from conventional farms was omitted. In order to sustain roughage yields and avoid changes in the feed plan, the feed crops received the same amount of plant-available N in the references and in all scenarios. The remaining N was applied to the cash crops. The grass–clover area, and thereby the area of crops having grass–clover as a pre-crop, differed between scenarios. In S1, grass–clover was followed by spring wheat, oats, maize, potatoes and winter wheat, in S2 the crop rotation used in the reference scenarios was used, and in S3 and S4 grass–clover was followed by spring wheat oats and maize.

The changed crop rotation and the use of biogas digestate as fertilizer affected the amount and quality of the fertilizer in the scenarios. Therefore, the yield of the cash crops and energy crops was adjusted depending on the amount of ammonia N applied to the individual crops. The yield response used was based on recommendations by DAAS[27] (Table 6). Only yields of cereals were adjusted, since manure application to feed crops was kept constant. Yields of potatoes and other cash crops, which comprise less than 5% of the area, were not adjusted due to lack of data on the N response of these crops in organic farming.

Anaerobic digester

CH_4 production in the FarmGHG model is determined by the equation: $P_{CH4} = \varepsilon\ VS\ B_o\ 0.67$, where P_{CH4} is the CH_4 production (kg), VS is the input of volatile solids to the digester (kg), B_o is the maximum methane-producing capacity of the added material ($m^3\,kg\,VS^{-1}$), ε is the efficiency of the process (0–1) and 0.67 converts from volume to kg of CH_4.[17] Methane-producing capacities of the materials used are showed in Table 7. Reliable values for ε were not found in the literature, but since practical yields generally are lower than B_o,[28] an efficiency of 0.9 was assumed.

The anaerobic digester specified in the FarmGHG model consists of three components: a pre-store tank, a digestion tank and a post-store tank (Table 7). In order to minimize GHG emissions from the tanks, it was assumed that both the pre-store and the post-store had a solid cover. This also reflects the general standard in Denmark[29]. The surface areas of the tanks were calculated from the volume of material added to the respective tanks in S1, assuming the height of the tanks was 6 m. The actual

Table 6. Yield adjustments with varying rates of ammonia N applied as slurry[27].

NH_4-N applied ($kg\,ha^{-1}\,yr^{-1}$)	0–50	50–100	100–150
Yield response ($kg\,dm\,kg^{-1}$ NH_4-N yr^{-1})			
Winter grain, standard	20	15	10
Winter grain, pre crop grass–clover	20	15	5
Spring grain, standard	20	10	0
Spring grain, pre crop grass–clover	5	0	0

Table 7. Parameters for anaerobic digestion used in FarmGHG.

Surface area, pre-store tank (m^2)	125
Surface area of post-store tank (m^2)	3000
Storage time, pre-store tank (days)	14
Digestion time (days)	25
Digestion efficiency, proportion of max. digestion	0.9
Maximum methane-producing capacity (B_o) ($m^3\,kg^{-1}$ VS)	0.21 (feces, heifers) 0.24 (feces, cows) 0.34 (grass–clover silage) 0.36 (maize silage) 0.30 (grass silage from meadows)
Methane loss during combustion, proportion	0.018
Production of electricity ($MJ\,kg^{-1}$ CH_4)	18.69
Production of heat ($MJ\,kg^{-1}$ CH_4)	26.70

amounts of organic matter in the stores varied between scenarios, but the surface areas were kept constant. Water was added to the digester to reach a dry matter level of 10% to make the material liquid enough for pumping[29].

The energy requirement of the anaerobic digester was defined based on Berglund and Börjesson[30]. They reported best estimates for continuous, single-stage, mesophilic tank reactors; a common reactor type in Denmark[29]. Heat and electricity inputs of 1100 and 660 MJ per ton dry matter were used.

The lower heating value of CH_4 ($35.8\,MJ\,m^{-3}$) was used to decide the energy production from the CH_4 produced in the digester. A total of 35% of the energy produced was assumed to be converted into electricity, 50% was converted to heat, whereas 15% was lost[29]. CH_4 loss from the anaerobic digester was set to 1.8%.[31]

Environmental impacts

The environmental impacts analysis focused on the direct energy balance, the N balance and the GHG emissions of the farm.

Energy use and production. Energy use on the farm included electricity for animal production ($400\,kWh\,cow^{-1}\,yr^{-1}$), for cleaning the floor ($40\,kWh\,cow^{-1}\,yr^{-1}$), and diesel for management of the fields as specified in the FarmGHG model[17]. Indirect energy use for production and provision of goods and services to the farm is not included in the analysis. Energy production on the farm was based on CH_4 production in the anaerobic digester. Since the biogas plant was on the farm, no transport to and from the biogas plant was included. However, energy for transport of imported slurry and biomass from meadows was calculated according to Dalgaard et al.[10] and added to the energy use. A transport distance of 6 km in total was assumed.

N balance and N loss. A farm N balance was calculated according to Watson et al.[32] using numbers extracted from the FarmGHG output files. N deposition was not included in the FarmGHG model, but an input of $15\,kg\,N\,ha^{-1}$ (equivalent to the average N depositions in Denmark in 2005[33]) was added to the N balance. The N input includes: slurry import, import of grass cuttings from meadows, feed, seed, N fixation and deposition. The N output includes: milk, meat and cash crops sold from the farm. The FarmGHG model estimates N losses in the form of nitrate leaching, ammonia volatilization and nitrous oxide emissions. The nitrate leaching is calculated as 30% of all N input to the field. The model SimDen[34] was used for quantification of denitrification in the soil. The model calculations are based on the amount of N applied and N source; in this case legumes, slurry and grazing livestock. The denitrification is quantified for various soil types and for three levels of organic matter in the soil. We assumed a medium level of organic matter in the soil, and used the mean of the denitrification rate from the model for the four classes of sandy soils in Denmark. Changes in the soil N pool were estimated by subtracting all N losses from the N surplus.

GHG emissions. The FarmGHG model uses Intergovernmental Panel on Climate Change (IPCC) standards for calculations of GHG emissions. In this case, the default methodology of the model was updated with the IPCC 2006 emission factors[35].

The GHG emissions calculated included emissions of N_2O, CH_4 and CO_2, both direct emissions from the farm and pre-chain emissions from import of energy, seed and feed. The import of slurry and organic matter from meadows is not associated with any pre-chain emissions, because these products are regarded as waste. CO_2 emissions for transportation of imported slurry and biomass from meadows were calculated from the diesel use according to Olesen et al.[17], and added to the CO_2 emissions calculated by FarmGHG. N_2O emissions included pre-chain emissions, emissions from slurry in the house and manure store, and emissions from the field. Also indirect N_2O emissions from N lost by nitrate leaching and ammonia volatilization were accounted for. The CH_4 emissions included pre-chain emissions,

Table 8. Manure use and crop yields for 1000 ha farms.

	Ref. A	Ref. B	S1: Grass–clover	S2: Maize	S3: Cash crops	S4: Meadows
Manure (Mg total N yr^{-1})						
Slurry, livestock	59.9	59.9	0	0	0	0
Biogas digestate, livestock	0	0	59.9	59.9	28.5	28.5
Biogas digestate, energy crop	0	0	17.7	11.0	35.4	43.7
Import (slurry or organic matter)	25.8	0	0	0	0	0
Total	85.7	59.9	77.6	70.9	63.9	72.2
NH_4-N for cash crops (% of N-norm)	46	0	80	12	45	59
N_2 fixation (Mg N yr^{-1})	93.2	93.1	117.8	92.9	95.8	95.8
Yields						
Total cash crop yield (Mg dm yr^{-1})	895	723	794	642	1493	1983
Total milk yield (Mg yr^{-1})	3953	3953	3953	3953	1881	1881
Cash crop yield (kg dm ha^{-1} cash crop yr^{-1})	3085	2492	3269	2642	3072	4080

emissions from enteric fermentation in the livestock, emissions from slurry in the house, emissions from the manure store and anaerobic digester, and emissions from feces excreted in the field. CO_2 emission or sequestration from changes in soil organic matter content is not included in the model estimation, since the farm system is assumed to be in steady state[17].

Results

N fluxes and yields

The amount of N available in the farm systems depended on the number of livestock, the grass–clover area, the energy crop used, and the import of slurry or organic matter (Table 8). The total amount of N available for application was higher in Reference A, where slurry and feed were imported, than in the four scenarios with use of digestate from the biogas production. In Reference B, it was not possible to sustain the fertilization of the roughage and no N was left for the cash crops. In S3 and S4, the increased amount of digestate from energy crops did not compensate for the lower livestock density and lack of slurry import when the total amount of N for application was considered. Although the total amount of N available for application was lower in the biogas scenarios, it was possible to apply NH_4-N to the cash crops in amounts equivalent to (S3) or higher (S1 and S4) than the amounts used in Reference A. Thereby increased cash crop yields were obtained in S1 and S4. Omission of import of manure in Reference B reduced total farm cash crop yield by 19% compared with Reference A. In S1 and S2, where the cash crop area was reduced due to the production of energy crops, the total cash crop yield was 11 and 28% lower than in Reference A.

Environmental impacts

Energy balance. Energy use, in the form of electricity and diesel, was higher in the biogas scenarios than in References A and B due to the energy requirement of the anaerobic digester (Fig. 2). This was, however, compensated for by the energy production of the anaerobic digester, and all biogas scenarios had a positive energy balance. The net energy production in the four scenarios was between 6274 GJ (S1) and 11,130 GJ (S4). This net energy production assumed that the heat was utilized and not wasted. In S3, where the area used for bioenergy production was doubled and the number of livestock was decreased, the net energy production was increased by 44% compared with S1.

N balance and N loss. The N surplus of the farm was between 79 and 107 kg N ha^{-1} (Table 9). N fixation was the largest single contributor to the N surplus. Other important factors affecting the N surplus were the amount of imported slurry or organic matter and the export of milk and cash crops. The export of N from the farm was at the same level in all scenarios; the decrease in export of milk and meat in S3 and S4 was compensated by an increase in export of cash crops. Another result of the larger cash crop area in S3 and S4 was that no import of feed was needed.

S2, S3 and S4 reduced the N-leaching loss by 7.7, 16.1 and 11.9%, respectively, compared with Reference A, and S1 increased the loss by 4.8%. N lost by denitrification followed a similar pattern. The NH_3 emissions were reduced by 18.9 and 22.5% in S1 and S2, when compared with Reference A. In S3 and S4, where the number of livestock was reduced, the reduction was 45.5 and 40.5%. The calculations showed a risk of decreasing amounts of N in the soil in Reference B and S2.

GHG emissions. The net GHG emission was reduced by the implementation of anaerobic digestion (Fig. 3). The net GHG emission of S1 and S2 was reduced to 64 and 62% of Reference A. In S3 and S4, a large reduction in net GHG emission (to 17 and 12% of Reference A) was mainly caused by reduced CH_4 emission from the reduced number of livestock (Fig. 4a). CH_4 emissions from the manure store were reduced by the anaerobic digestion, but the loss of CH_4 from the biogas plant resolved part of this

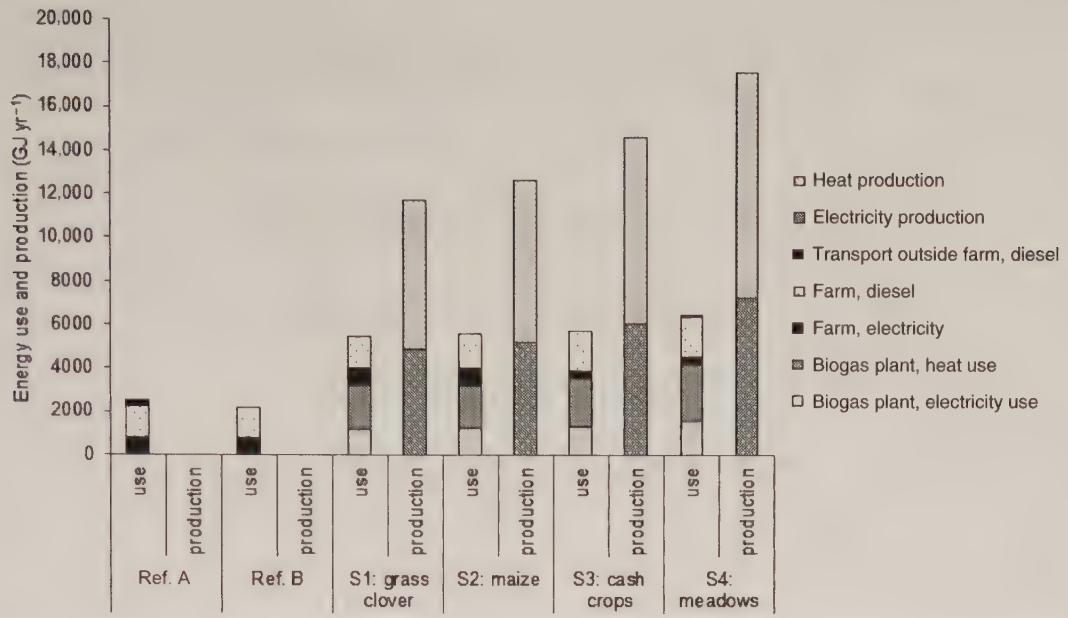

Figure 2. Use of electricity and diesel and production of electricity and heat. Diesel use for transport includes solely the consumption in relation to the external import of slurry and meadow grass.

reduction. Seventy percent (S2) to 96% (S4) of the N_2O was emitted from the field (Fig. 4b). The N_2O emission from the manure store was slightly higher in the biogas scenarios than in the reference scenarios, partly due to indirect emission caused by larger ammonia emissions. The pre-chain emission of N_2O was reduced considerably in S3 and S4, where no feed was imported. Biogas production reduced the indirect emissions of CH_4 and N_2O connected to transport and production of diesel and electricity, illustrated by a small negative emission. CO_2 emission was in all scenarios smaller than the reduction in CO_2 emissions from fossil fuels caused by the biogas production (Fig. 4c).

Discussion

Manure availability and yields

The current import of slurry from conventional farms to organic farms in Denmark is represented by 25.8 kg total N ha^{-1} imported in Reference A. The use of 10% of the land for bioenergy production in S1 and S2 does not produce enough digestate to compensate for this import: grass–clover contributes 17.7 kg N ha^{-1}, whereas the contribution of maize is just 11.0 kg N ha^{-1} (Table 8). However, the annual N fixation of 100 ha grass–clover energy crop in S1 corresponds to 24.9 Mg N and the total N input to the farm is therefore at the same level as in Reference A. Therefore, when the lower cash crop area and the higher fertilizer replacement value of the digestate are taken into consideration, use of grass–clover for biogas increases the amount of N available to the cash crops (Table 8). On the other hand, maize does not provide extra N to the farm, but requires N fertilization to obtain high yields. This causes a lower total input of N to the farm in S2, and the yields of the cash crops are reduced. Based on this, grass–clover seems to be the most realistic option for biogas production in organic agriculture, assuming that the energy crop should contribute both to energy supply and improve N availability on the farm.

In the present study, grass–clover for biogas production was fertilized despite the high amount of N fixed by the clover. Grass–clover yields respond positively to N application, but the N response of grass–clover is variable and dependent on a number of factors, including the share of clover in the field and the age of the grass–clover crop[26]. Relatively high yields (7.1–7.8 Mg dm yr^{-1} on average) have been reported without any N application[26]. Therefore, a better strategy for production of grass–clover as an energy crop might be to omit fertilization and spare the N for the cash crops.

Analysis of the geographical distribution of organic dairy and cash crop farms in Denmark shows that the cash crop farms are only to a limited extent placed in the same regions as dairy farms[7]. Therefore most cash crop farms depend on either import of slurry from conventional farms or on N-fixing crops as a source of N to the crop rotation. In S3, 100 ha grass–clover provides enough N to sustain a doubling of the cash crop area (from 243 to 486 ha). In Reference A, the cash crops receive on average 63 kg total N ha^{-1}, equivalent to 30 kg plant-available N (Table 3). The 100 ha grass–clover field in S1 yielded 17.7 Mg N yr^{-1}. This corresponds to a harvest of 106–123 kg plant-available N ha^{-1} yr^{-1} (assuming a content of 60–70% plant-available N in the digestate). Usage of the digestate from 1 ha grass–clover provides enough N for 3.5–4.1 ha cash crops, maintaining the amount of N

Table 9. Farm N balance (kg N ha^{-1} yr^{-1}).

	Ref. A	Ref. B	S1: Grass clover	S2: Maize	S3: Cash crops	S4: Meadows
Input						
Slurry import	25.8	0	0	0	0	0
Organic matter	0	0	0	0	0	8.3
Feed	7.0	8.4	7.3	8.8	0	0
Seed	1.2	1.2	1.1	1.1	1.6	1.6
N fixation	93.1	93.1	117.8	92.9	95.8	95.8
Deposition	15.0	15.0	15.0	15.0	15.0	15.0
Total input	142.1	117.7	141.2	117.8	112.4	120.7
Output						
Milk	20.8	20.8	20.8	20.8	9.9	9.9
Meat	2.6	2.6	2.6	2.6	1.2	1.2
Cash crops	12.6	10.9	10.4	9.2	22.3	23.2
Total output	36.0	34.3	33.8	32.6	33.4	34.3
Farm N surplus	106.1	83.4	107.4	85.2	79.0	86.4
N loss, house and manure store	3.2	3.2	3.9	3.8	1.4	2.6
Field N surplus	102.9	80.2	103.5	81.4	77.6	83.8
Denitrification	10.4	9.1	10.8	9.7	8.8	9.2
NO_3 leaching	60.9	53.1	65.7	56.2	51.1	53.6
NH_3 emission	22.2	16.4	18.0	17.2	12.1	13.2
Soil N change	9.4	1.6	9.0	−1.7	4.6	7.8

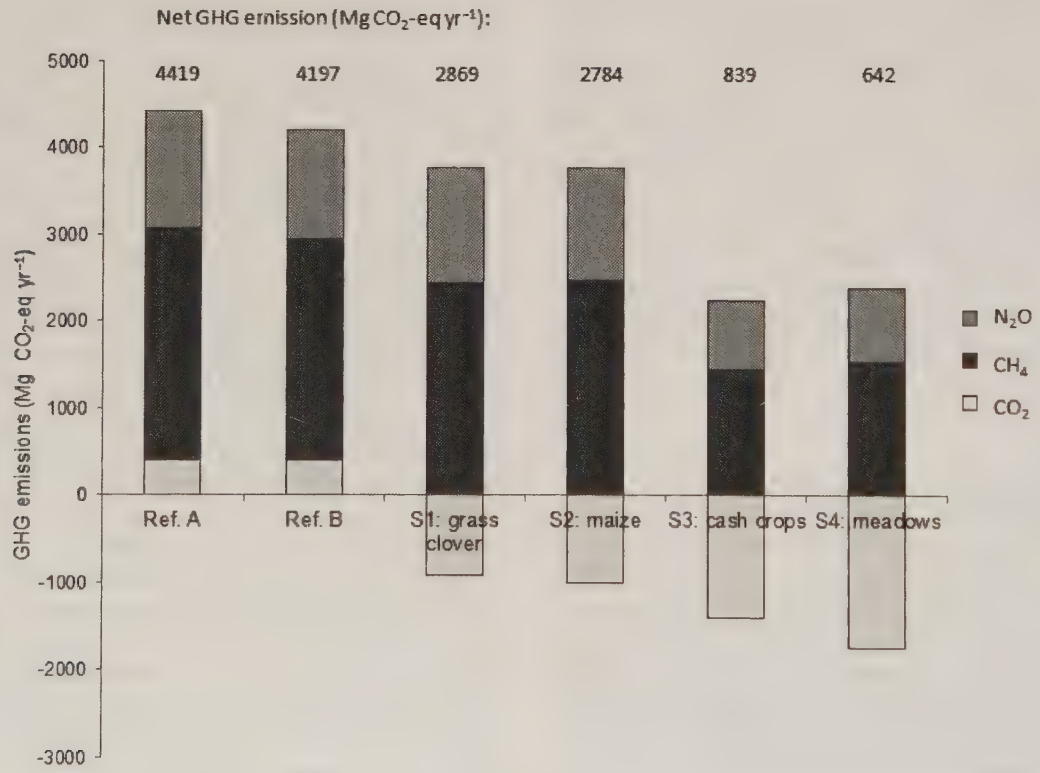

Figure 3. Net emission of N_2O, CH_4 and CO_2 from the 1000 ha farm. The numbers above the columns show the total net GHG emission.

currently applied in organic agriculture in Denmark. This corresponds to approximately 20% of the farm area. Based on this, biogas production has the potential to make organic cash crop producers independent of conventional manure and thereby contribute to an increase in the organic cash crop area, as suggested by Tersbøl[13]. In another study of anaerobic digestion of grass–clover in organic cash crop farming systems by Stinner et al.[12], 1/6

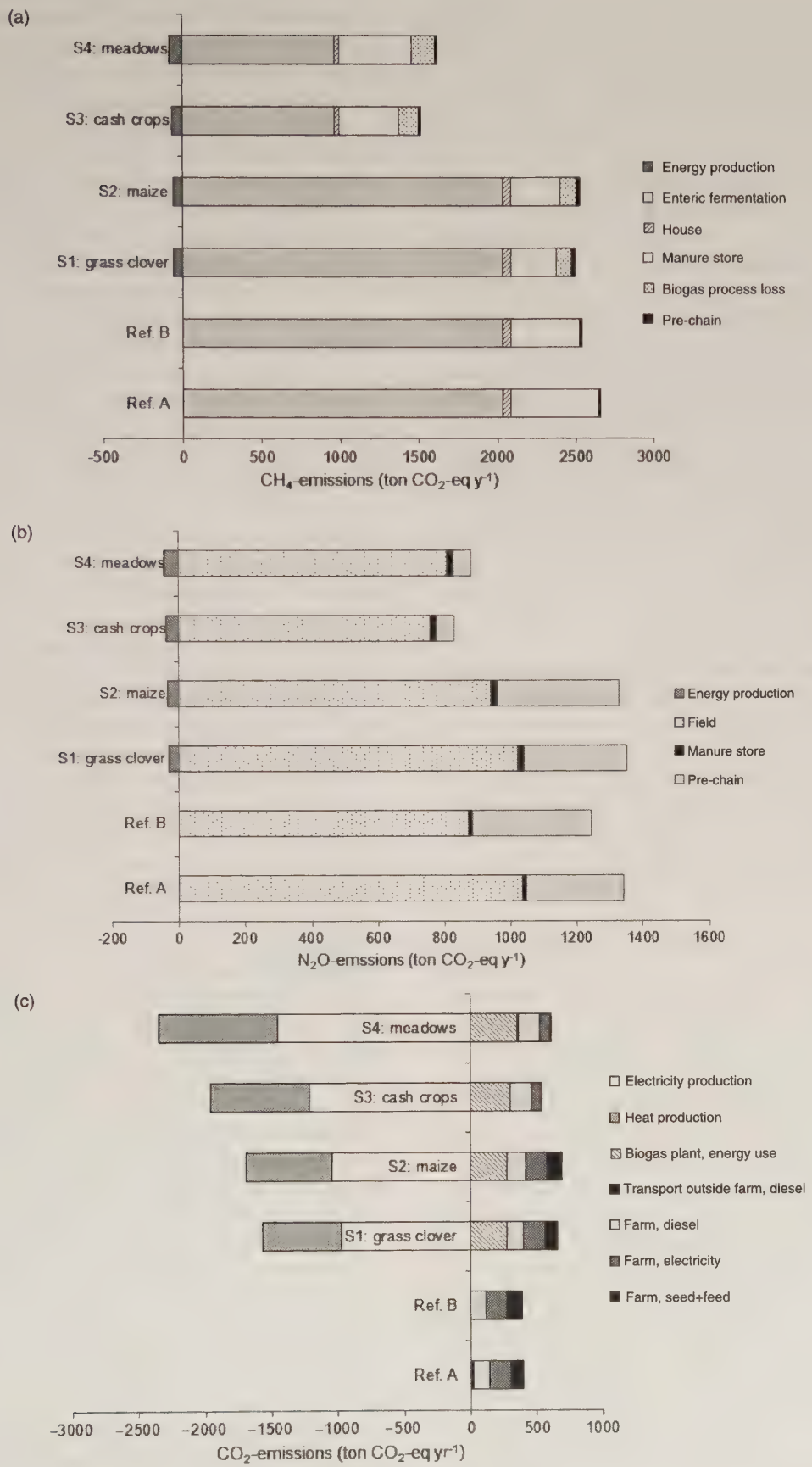

Figure 4. Emissions of (a) CH_4, (b) N_2O and (c) CO_2 for the 1000 ha farm divided into origin and expressed in CO_2 equivalents.

of the area was used for grass–clover. Here, the grass–clover was digested in combination with cover crops and crop residues. Thereby more N was recycled in the digestate and on average 125 kg total N ha^{-1} was supplied to the cash crops, showing that the N potential of the current study is perhaps conservative.

The use of organic matter from meadows in S4 provides an additional option for provision of N, as well as other nutrients, to the system. In a system with export of cash crops, but without external imports (e.g., manure and feed), essential nutrients are removed from the system. In the long term, the risk is that soil nutrient reserves [e.g., phosphorus (P) and potassium (K)] are depleted, as demonstrated by Gosling and Shepherd[36]. Another study by Møller and Nielsen[37] suggested that 100,000 ha meadows are suitable for harvest of biomass for bioenergy production in Denmark; and therefore an area of 200 ha of meadow for a 1000 ha organic farmland is not unrealistic. However, accessibility, yield and interest of the plot owners are important factors that must be investigated to clarify the actual potential.

Environmental impacts

Energy balance. The 1000 ha farm model has an energy surplus, but import of diesel is still necessary to fuel the farm machinery. In that sense energy self-sufficiency is not obtained. In Denmark, biogas is generally used for combined heat and power production, and the heat used for district heating[28]. As the heat requirement on farm is limited, it is important to be aware that the placement of the biogas plant is restricted to locations with possible applications of the heat, e.g., urban areas with district heating. This conflicts with the assumption that the biogas plant is placed on the farm. Alternatively the biogas could be upgraded for distribution in the natural gas network in Denmark or used as a gaseous transport fuel, as suggested by Smyth et al.[38].

The electricity requirement of the farm is very low compared with other investigations, where electricity use on dairy farms 4–5 times higher than the value used in FarmGHG has been reported[8,9]. However, energy companies advise farmers to reduce their electricity use if it exceeds 800 kWh cow^{-1} yr^{-1} (Kurt Mortensen, personal comment). The default value used by FarmGHG (440 kWh cow^{-1} yr^{-1}) is perhaps optimistic, but was used due to a lack of more reliable data.

Energy costs of transport of biomass to and from the digester, apart from the imported biomass from meadows in S4, were neglected as a single farm structure with short distances was assumed. In a study by Gerin et al.[39], 10 km transport of maize and grass–clover silage to a centralized biogas plant affected the energy balance by only 4–6%. However, the energy ratio (GJ produced/GJ used) was decreased by 40–50%.

N balance and N loss. The N balance of Reference A represents an average of organic farms on sandy loam in Denmark in 2006. Since arable farms and dairy farms are combined, it is difficult to compare the results with other studies where dairy farms and arable farms are analyzed separately (e.g., Knudsen et al.[40]). For comparison, the annual farm N surplus of 47 organic farms in different countries ranged between 2 and 196 kg N ha^{-1} yr^{-1},[32] while our scenarios ranged from 79 to 106 kg N ha^{-1}.

The nitrate-leaching loss was calculated as 30% of all N input to the field and is the same for all crops and crop rotations. It is well known that crop type and management play an important role for N-leaching losses. Askegaard et al.[41] found that leaching losses in an organic crop rotation depended on field management during autumn and winter. Smallest losses (on average 20 kg N ha^{-1}) were observed when the soil was covered by cover crops during autumn and winter and highest losses were observed after stubble cultivation in autumn (on average 55 kg N ha^{-1}). This indicates that management including cover crops would reduce N-leaching losses in all scenarios. In addition, use of cover crops could contribute to the biogas production and facilitate recycling of nutrients assimilated by the cover crop.

In general, the share of grass–clover in the crop rotations was high, 34–44%. Large amounts of N are often lost after plowing of grass–clover swards, especially if followed by winter wheat[42]. Large areas of grass–clover in the crop rotations make management to reduce nitrate leaching more complicated. Since spring cereals are usually used for the establishment of grass–clover, there is a risk that grass–clover is to a greater extent followed by winter cereals. This is the case in S1. Therefore the crop rotations in S3 and S4 are more suitable for anaerobic digestion of grass–clover than S1, where large areas of grass–clover are already needed to supply grass–clover for the livestock.

GHG emissions. The largest contributions to the farm GHG emissions are CH_4 emissions from enteric fermentation and N_2O emissions from the field. Since the same feed intake is used in all scenarios, CH_4 emissions from enteric fermentation depend exclusively on the number of animals on the farm. N_2O emissions from the field depend of the amount of N added as slurry and digestate, and are therefore only affected by implementation of anaerobic digestion if lower amounts of total N are applied to the field due to the higher fertilizer value of the digestate. Another important factor for the N_2O emission is pre-chain emissions connected with the imported feed, which is affected by the number of animals and the area for cash crop production on the farm. Therefore, apart from the reduced CO_2 emissions, only emissions from the manure store are directly influenced by implementation of the anaerobic digester.

Field studies of the N_2O emissions from cattle slurry compared with digested slurry are ambiguous. Carter et al.[43] found emission factors at the same level for slurry and digested slurry, whereas Möller and Stinner[44] found higher emission from digested slurry than from raw cattle

slurry. The calculated emissions of N_2O from the field are based on emission factors[17] assuming 1% of added N is emitted as N_2O.[35] In practice, N_2O emissions are highly variable, and affected by, for example, tillage and soil type[43,45]. NO_3 leaching is a large contributor to indirect N_2O emissions from the field and reductions in NO_3 leaching, as described in the section 'N balance and N loss', would therefore also reduce N_2O emissions.

Loss of CH_4 from the anaerobic digester affects the GHG balance of the system significantly. If the CH_4 emission from the biogas plant increases from 1.8 to 2.8%, it will increase the GHG emission from the biogas plant (including manure stores) by 14.4% and the total GHG emission from the farm by 2.3%. In the current study, a loss of 1.8% is assumed, but other studies indicate that the loss might be higher: Kvist calculated a loss of 2.2% from the gas engine alone (personal communication, calculations based on results from Kvist et al.[46]). In addition, there is loss from the manure stores. Börjesson and Berglund[47] used a total loss of 1% of the produced CH_4, but also estimated that if 10–20% of CH_4 produced was lost, it would cause a GHG emission from the biogas system at the same level as the emission from fossil fuels. Thus, the CH_4 loss from the biogas chain is an important factor to be aware of when environmental impacts of biogas systems are analyzed. Efforts to reduce the loss will significantly improve the biogas GHG balance.

Anaerobic digestion is connected to a loss of organic C as it is converted to CH_4. In a study of the influence of biogas digestion on soil organic matter, Möller[48] found that digestion of slurry and crop residues reduced the overall soil C supply by approximately 33%. Both C incorporated directly into the soil as crop residues or cover crops and C added as slurry or digestate were taken into account. The amount of C added as slurry or digestate increased when slurry and crop residues were digested, but this was counteracted by a decrease in C incorporated directly into the soil. The amount of C applied was still enough to replace degradation of soil organic matter and maintain a positive C balance. In the current study, the amount of C added to the soil as slurry or digestate varied between 0.45 and 0.54 $Mg\,ha^{-1}$ in the reference scenarios and 0.47–0.56 $Mg\,ha^{-1}$ in the biogas scenarios (S2 and S4). This indicates that soil C changes due to change in applied C are not likely to happen. However, the risk of negative impact on soil N in S2 (Table 9) indicates a risk of a concurrent decline in soil C.

Conclusion

Implementation of biogas digestion changes the N flows on the farm by introducing new N sources from legume-based energy crops. The amount of NH_4-N available for application on the farm cash crops increased when grass–clover was used for biogas production, but decreased when maize was used. A positive farm energy balance was obtained for all biogas scenarios, showing that biogas production on 10% of the area provides an energy surplus on the farm. Substantial reductions (up to 72%) in net GHG emissions were obtained as well. Biogas production on organic farms holds the possibility for the farms to achieve a positive energy balance and to provide self-sufficiency with organic fertilizer.

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Nitrogen fertility in semiarid dryland wheat production is challenging for beginning organic farmers

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Abstract

Organic farming systems use green and animal manures to supply nitrogen (N) to their fields for crop production. The objective of this study was to evaluate the effect of green manure and composted cattle manure on the subsequent winter wheat (*Triticum aestivum* L.) crop in a semiarid environment. Dry pea (*Pisum sativum* L.) was seeded in early April and terminated at first flower in late June. Composted cattle manure was applied at 0, 11.2 or 22.5 Mg ha^{-1} just prior to pea termination. Winter wheat was planted in mid September following the green manure or tilled summer fallow. No positive wheat response to green manure or composted cattle manure was observed in any of the 3 years of the study. In 2 of the 3 years, wheat yields and grain test weight were reduced following green manure. Green manure reduced grain yields compared with summer fallow by 220 and 1190 kg ha^{-1} in 2009 and 2010, respectively. This may partially be explained by 40 and 47 mm less soil water at wheat planting following peas compared with tilled summer fallow in 2008 and 2009, respectively. Also, in 2008 and 2009, soil nitrate level averaged 45 kg ha^{-1} higher for black fallow compared with green manure fallow when no compost was added. Organic growers in the semiarid Central Great Plains will be challenged to supply N fertility to their winter wheat crop in a rapid and consistent manner as a result of the inherently variable precipitation. Growers may need to allow several years to pass before seeing the benefits of fertility practices in their winter wheat cropping systems.

Key words: organic farming, green manure, composted manure

Introduction

In the semiarid portions of Central Great Plains, dryland agriculture has developed around winter wheat production. A variable climate with unpredictable precipitation has made dryland farming in the region inherently risky[1,2]. Summer fallow, the practice of controlling all plant growth during the non-crop season, was quickly adopted in the region to increase the chances for successful establishment and development of winter wheat and to stabilize winter wheat yields[3]. However, frequent use of summer fallow, especially when mechanical tillage is used, can result in severe soil erosion, reduced soil carbon and quality, and reduced grain yields and protein content in cereal crops[4].

Organic farming systems frequently rely on biological N fixation from *Rhizobium* bacteria in symbiotic association with legume species that are used as green manure[5]. The release of N from plant residues is dependent on several factors that include chemical composition and N concentration, temperature and soil water availability[6]. Optimum temperatures and moisture are required for good decomposition and typically occur when soil moisture content is between 50 and 100% of field capacity and when soil temperatures are between 25 and 32°C[7]. The major challenge to the use of green manure crops in semiarid agriculture is balancing the trade-off between water use by the green manure crop, which will not be available for the following winter wheat crop, and the potential N benefit to the winter wheat crop.

Long-term assessments of lentil (*Lens culinaris* Medikus) green manure as a partial summer fallow replacement in conventional, i.e., non-organic, cropping systems have been conducted in the US Northern Great Plains and Canadian Prairies. In the first half of a 12-year study conducted at Swift Current, Saskatchewan, lentil was planted in May and turned down at full bloom (late July or early August) to maximize N fixation[8]. Subsequent

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spring wheat yields were reduced compared with traditional summer fallow as a result of soil water depletion by lentil. However, in the second half of the study, lentil was planted in April and turned under in early July to reduce water consumption. Subsequent spring wheat yields in the second half of the study were similar between green manure and traditional fallow, plus there was a gradual increase in wheat grain protein and a gradual decrease in N fertilizer requirement following lentil. In Montana, a similar 12-year study was conducted with lentil as a partial summer fallow replacement[9]. Although the authors did not see a difference in starting soil water for spring wheat following green manure killed at full bloom or fallow, they did see reduced grain yield following green manure in the first 5 years, which they explained by low soil nitrate following green manure. In the last 6 years of the study, grain yields following green manure and fallow were similar and the green manure treatment had 26% greater spring soil nitrate than fallow.

In a conventional production system in Colorado, winter wheat yield following annual legume green manures [Austrian winter pea (*Pisum sativum* L. subsp. *sativum* var. *arvense* (L.) Poir.), spring field pea and black lentil] was reduced from 400 to 1050 kg ha^{-1} compared with summer fallow depending on the termination date of the green manure[10]. Water use by the green manure explained 88% of the variability in winter wheat yield. The benefits of green manure fallow were highly weather-dependent and inconsistent. The impact of replacing summer fallow in a no-till production system with various spring-planted crops prior to winter wheat seeding was studied in western Nebraska[11]. Winter wheat yields following summer fallow replacement crops were reduced from 22 to 58% following oat (*Avena sativa* L.) + pea for forage and corn (*Zea mays* L.), respectively, compared with wheat following summer fallow. This was largely explained by a 27–41% reduction in soil water at wheat planting following these two crops compared with following summer fallow. Winter wheat yield has been reported to be strongly correlated with the available soil water at wheat planting[12].

In a dryland organic wheat system in Montana, winter wheat yield and quality were higher following winter pea green manure than spring pea green manure[13]. Winter pea had greater shoot N content when terminated at the pod stage, contributed greater soil nitrate-N, and used less soil water than spring pea. Termination timing, either at bloom or pod stages, was of secondary importance to pea type.

Animal manures are widely used to fertilize crops and increase soil organic matter content. Nitrogen content of manure is affected by animal species, feed, bedding, and manure storage and handling. The average apparent first-year N availability for corn was 57, 53, 14 and 4% for fresh poultry, dried poultry, composted poultry and composted cattle (*Bos taurus*) manure, respectively[14]. Corn yield following composted cattle manure was no different than the no N control treatment. Apparent N and phosphorus recovery in barley (*Hordeum vulgare* L.) was lower for fresh and composted beef cattle manure (5–9%) than for inorganic fertilizer (22–47%)[15]. The gradual N release from fresh and composted manures, as opposed to the quick release of inorganic N fertilizer, over several years benefitted weed growth more than spring wheat[16].

Organic growers are restricted to using organic certified N sources. In a semiarid environment such as Sidney, NE, conversion of these organic N sources to nitrate–N may be slower than in a more humid environment. The objective of this study was to ascertain the impact that green manure pea and composted cattle manure had on winter wheat yield and grain quality characteristics in a certified organic production system in the semiarid Central Great Plains.

Materials and Methods

Studies were conducted in fields certified through the Organic Crop Improvement Association in 2006 at the University of Nebraska–Lincoln High Plains Agricultural Laboratory (41°12′N, 103°0′W, 1315 m elevation above sea level) located near Sidney, NE. The certified organic land is divided into three 10-ha fields managed in a 3-year rotation of winter wheat–proso millet (*Panicum miliaceum* L.)–green manure fallow. Each year, a new study was established in the field with green manure fallow. Soils were an Alliance silt loam (fine-silty, mixed, superactive, mesic Aridic Argiustolls) in 2008/2009 and a Duroc loam (fine-silty, mixed, superactive, mesic Pachic Haplustolls) in 2009/2010 and 2010/2011. Soil pH in the surface 20 cm was 7.3, 6.6 and 7.0 for 2008/2009, 2009/2010 and 2010/2011, respectively. Soil organic matter content in the surface 20 cm was 23, 27 and 27 g kg^{-1}, respectively.

A split-plot experimental design was used. Whole plot treatments were replicated four times in a randomized complete block design and consisted of green manure fallow and conventional tilled fallow (black fallow), and subplots consisted of one of three levels of composted cattle manure (0, 11.2 or 22.5 Mg ha^{-1}). Whole plots were 9 m × 9 m and subplots were 3 m × 9 m. Forage pea '4010' was used as the green manure crop. Peas were treated with the peat formulation of Cell-Tech pea and lentil (Novozymes BioAg, Inc., Brookfield, WI) and planted in early April at a depth of 7.5 cm in 25-cm rows and at a seeding rate of 67 kg ha^{-1}. Peas were allowed to grow until first flower, which occurred during the last 2 weeks of June, and then terminated with a tandem disc operated to a 10-cm depth. This was followed by a chisel plow with small sweep points and then a rod weeder for the remainder of the fallow period. Immediately prior to pea termination, pea biomass was randomly collected from 1 m^2 per replication to estimate pea biomass. Pea biomass was dried at 50°C until a constant weight was achieved. Also, at this time, composted manure

Table 1. Precipitation during the pea, fallow and winter wheat phases of the field study conducted at Sidney, NE from 2008 to 2011.

Crop phase	2008–2009	2009–2010	2010–2011
	mm		
Peas	112	313	205
Fallow	159	115	108
Winter wheat	412	406	440
Total	683	834	753

Table 2. Winter wheat grain yield and soil water in surface 122 cm of soil at wheat planting following green manure and black fallow at Sidney, NE from 2008 to 2011.

	Grain yield			Soil water		
Treatment	2009	2010	2011	2008	2009	2010
	kg ha^{-1}			mm		
Green manure fallow	2990	4020	4570	143	178	277
Black fallow	3210	5210	4530	183	225	264
P-value	0.021	0.044	0.776	0.008	0.017	0.063

Table 3. Soil nitrate–N in the surface 120 cm of soil before winter wheat planting and following green manure and black fallow at Sidney, NE from fall 2008 through 2010.

Treatment	2008[1]	2009	2010
	kg N ha^{-1}		
Green manure fallow			
No compost	80a	121c	121b
11 Mg ha^{-1} compost	78a	253a	167a
22 Mg ha^{-1} compost	104a	219ab	146ab
Black fallow			
No compost	111a	179b	122b
11 Mg ha^{-1} compost	110a	194b	125b
22 Mg ha^{-1} compost	102a	223ab	144ab

[1] Means within a column followed by the same letter are not significantly different at the 5% probability level.

Table 4. Winter wheat grain moisture and test weight following green manure and black fallow at Sidney, NE from 2009 to 2011.

	Grain moisture			Grain test weight		
Treatment	2009	2010	2011	2009	2010	2011
	g kg^{-1}			kg m^{-3}		
Green manure fallow	131	96.9	106	723	767	762
Black fallow	108	99.3	107	779	779	767
P-value	0.014	0.037	0.660	0.014	0.024	0.255

treatments were applied to designated plots. Black fallow plots were tilled twice with a tandem disc and then once or twice with a chisel plow with small sweeps and then a rod weeder.

Composted cattle manure was stockpiled to provide fertilizer to the experiment for 3 years. The compost contained 9.5 g N kg^{-1}, 6.7 g P kg^{-1}, and 11.8 g K kg^{-1} on a dry matter basis. The compost application rates provided a total of 94 and 188 kg N ha^{-1} each year on an as-applied basis (12% moisture content), but only 10–20% of this would mineralize during the crop growth cycle[17].

Immediately prior to winter wheat planting, a soil sample was taken from the middle of each plot with a hydraulic soil probe using a 5-cm diameter sampling tube. Soil depth increments were: 0–20, 20–60 and 60–120 cm. A portion of each sample from every plot was used to determine gravimetric soil water content, while a second portion was air dried and analyzed for soil nitrate concentration. Gravimetric soil water content was converted to volumetric water content by multiplying by the soil bulk density for each depth layer.

Winter wheat 'Goodstreak' (2008) and 'Hatcher' (2009 and 2010) were planted at a rate of 56 kg ha^{-1} in mid September at a depth of 5 cm and a row spacing of 30 cm. Immediately prior to wheat harvest in mid July, 2 m of row were clipped at ground level and removed from each plot to determine harvest index. Wheat straw from these samples were subsequently ground and analyzed for total N. Plots were mechanically harvested with a plot combine and yield determined from an area 2.0 m wide × 7.6 m long. Grain moisture and test weight were determined and a portion of the grain was analyzed for N content. Grain protein was calculated from grain N content using 5.7 as the multiplier. Total N removal was calculated by adding the N content of the grain and straw.

Data were analyzed using the General Linear Model (GLM) procedure in SAS[18]. Replications were treated as random effects. All other factors in the model were treated as fixed effects. Significant year by treatment interactions were observed, so data were analyzed separately by year. Treatment means were separated using Fishers' protected LSD at the 0.05 probability level.

Results and Discussion

Growing season precipitation, from pea planting through winter wheat harvest, varied from a low of 683 mm in 2008/2009 to a high of 834 mm in 2009/2010 (Table 1). The 30-year average total precipitation for Sidney from 1 April (pea planting) through June of the following year (winter wheat harvest) is 522 mm.

Fallow treatments

Winter wheat yields were higher following black fallow than green manure fallow in 2 of the 3 years (Table 2).

Table 5. Winter wheat grain N removal and total N removal (grain and straw) following green manure and black fallow at Sidney, NE from 2009 to 2011.

Treatment	Grain N removal			Total N removal		
	2009	2010	2011	2009	2010	2011
	---------- kg N ha^{-1} ----------			---------- kg N ha^{-1} ----------		
Green manure fallow	63.5	81.3	97.5	87.8	120	145
Black fallow	68.4	104	92.9	94.8	154	136
P-value	0.086	0.057	0.126	0.094	0.082	0.135

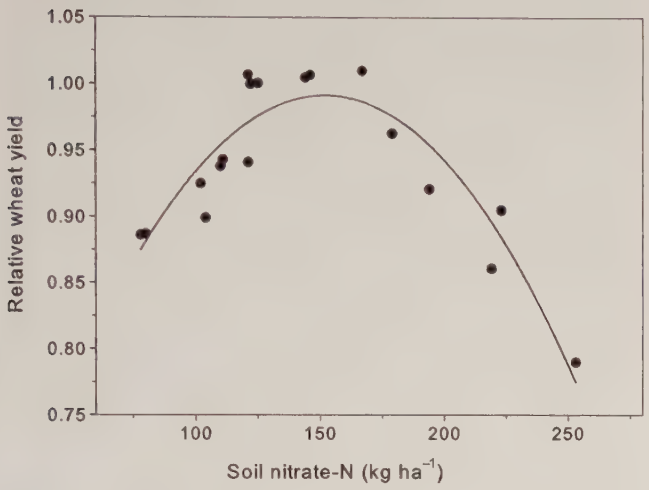

Figure 1. Predicted relative winter wheat yield versus soil nitrate–N (SN) and pre-plant soil water (SW) in the upper 1.2 m of soil. Equation: $Y = 0.64 + 0.00254SN - 0.000094SN^2 + 0.00077SW$, $R^2 = 0.47$.

There was no difference in winter wheat yield between black fallow and green manure fallow in 2011. Soil water prior to winter wheat seeding was at least 40 mm higher after black fallow than after green manure fallow in the first 2 years of the study when winter wheat yields were best following summer fallow. This is in agreement with the findings of Nielsen et al., who found that winter wheat yields were correlated with water at planting and that the elimination of summer fallow reduced soil water at planting and subsequent wheat yield[12]. In 2010/2011, there was less than 20 mm difference in soil water between the two fallow treatments and there was no significant yield difference (Table 2).

Soil nitrate levels were also different between black fallow and green manure fallow treatments receiving no manure (Table 3). Soil nitrate in the fall of 2008 and 2009, on average, was 45 kg ha^{-1} higher for black fallow compared with green manure fallow. The green manure crop not only reduced soil water but also soil nitrate. The N was not lost, but taken into the pea biomass. The dry matter accumulation averaged 1920, 1190 and 1420 kg ha^{-1} for 2008, 2009 and 2010, respectively. The above-ground N content averaged 60, 42 and 44 kg ha^{-1}, which varied due to available soil water. This N would be available later, but the delay in N release in addition to less soil water contributed to reduced grain yield.

Winter wheat grain moisture also varied by year (Table 4). In 2009, grain moisture was less after black fallow than green manure fallow. This was likely the result of wheat plants having less drought stress following black fallow than green manure fallow, which allowed the crop to mature more quickly following black fallow than after green manure fallow. Although the difference in grain moisture levels was statistically significant in 2010, from a practical standpoint, the small difference between treatments was of no significance. In 2011, no difference in grain moisture content was observed.

Grain test weight was higher following black fallow than green manure fallow in 2009 and 2010 (Table 4). In 2011, there was no difference in grain test weight. Test weight is an important quality trait used in the wheat industry and low test weights can result in significant price reductions for grain.

Grain protein averaged 138, 127 and 133 g kg^{-1} in 2009, 2010 and 2011, respectively. Although there were no differences in grain protein content between fallow treatments (data not shown), grain N and total N removal were higher following black fallow than green manure fallow in 2 out of 3 years (Table 5). This was likely the result of greater grain yields following black fallow in the first 2 years of the study.

Manure applications

There were no differences observed between manure treatments in this study. This was likely the result of a short time between manure application and winter wheat planting, and the relatively dry conditions during this time (Table 1), which prevented sufficient release of N from the composted cattle manure. Apparent N recovery in barley was only 5–9% following fresh and composted beef cattle manure[15]. This low recovery rate, combined with adequate soil N from the mineralization of soil organic matter, particularly following black fallow, resulted in no effect of composted cattle manure on the following winter wheat crop.

We saw no benefit from either green manure or composted beef cattle manure on the following winter wheat crop. In fact, in 2 out of 3 years, green manure

fallow decreased winter wheat grain yield, at least in part, as a result of soil water depletion prior to winter wheat planting. This agrees with the findings of Vigil and Nielsen from their work in eastern Colorado[10]. The other factor related to reduced grain yield and N removal was diminished nitrate in the fall of 2008 and 2009 after green manure fallow. The relationship between winter wheat yield and N application depends on the availability of both N and soil water. In soils with adequate N but insufficient water, yields are depressed, as in 2009. If N fertility is great enough, especially with limited water, the N response curve is curvilinear[19]. Figure 1 shows this relationship clearly for this experiment. Yields of each year were normalized to relative yield and compared with soil nitrate before wheat planting. Yield was maximized near $150\,kg\,ha^{-1}$ and higher nitrate levels tended to suppress yield, which was similar to results from Halvorson et al.[19]. A multiple regression equation relating relative yield to soil nitrate and preplant soil moisture had an R^2 of 0.47. The equation is

$$Y = 0.64 + 0.00245SN - 0.0000094SN2 + 0.00077SW,$$

where SN is kg soil nitrate–N in 1.2 m (Table 3) and SW is mm of preplant soil water (Table 2). The comparison of actual and predicted relative yield is shown in Figure 1.

Zentner et al. and Allen et al. did not see the benefits of green manure in their long-term field experiments during the first 5 or 6 years[8,9]. Our study suggests that growers in the semiarid Central Great Plains are unlikely to see the benefits of green manure or composted cattle manure on the immediately following winter wheat crop. In fact, as a result of the soil water used by green manure crops, winter wheat yields will often be negatively impacted by the use of green manure crops used as a partial summer fallow replacement. This is supported by the work of Nielsen et al.[12]. Organic wheat growers in the semiarid Central Great Plains may prefer the use of fresh manure, with its higher N content relative to composted manure. The use of green manures, which use valuable soil water, may be too risky in semiarid winter wheat production. As is often the case in organic production systems, semiarid winter wheat growers may need to be patient and be willing to accept some negative results in the early years of their production systems in order to see the benefits of these practices in their cropping systems.

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Farmers' experiments in Cuba

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Abstract

Due to the collapse of the socialist systems in 1989, Cuba's government promoted a series of structural changes to deal with resource scarcity and to enhance agricultural productivity. The upcoming crisis triggered adaptation strategies and led to a large-scale transition process towards a more sustainable model of agriculture. Farmers' experiments have been an implicit part of this process. Nowadays, farmers' capacity to experiment is widely accepted among the scientific community. However, detailed descriptions of farmers' approaches to experimentation are scarce. In this study, we examine the topics, resources, sources, motives, methods and outcomes of farmers' experiments in Cuba. The research methods comprised semi-structured interviews with 72 Cuban farmers, field notes, participant observation and a research diary. Key informants and 34 expert interviews added important insights into analysis. The results reveal that farmers' experiments are an integral part of farming in Cuba. Most farmers reported realizing their own experiments on their farms. The use of locally available resources was a crucial element for farmers' experiments. The topics were related to the introduction of new plant species or varieties, plant production, mechanization, fertilization, plant protection and the introduction of new animal species. The farmers' own idea was the most important source for experimenting, followed by ideas offered by colleagues and family members. Increasing production, independence from external resources and improving farm management were the main motives for experimenting. More than half of the farmers started to experiment without detailed written or mental planning, but made some considerations about the experiment before starting. Some planned more in detail and a few farmers devised a written plan, draft or model. Starting on a small scale was a way to minimize risks. The experiments were mainly evaluated by observation and comparison. Only a few farmers took records of their experiments. The most important outcomes were higher production, food self-sufficiency, work easement, improved plant health, increased knowledge, higher working efficiency and better taste of products. Farmers' experiments are a means of learning and they enhance farmers' capacity to adapt to changing conditions.

Key words: local knowledge, farmers' innovations, adaptive capacity, experimental process, sustainable agriculture, change, learning

Introduction

The collapse of the socialist systems

Before the collapse of the socialist systems in 1989, Cuba's agriculture was based on high levels of external inputs, which caused high external dependence. Agriculture was specialized on just a few crops cultivated in large-scale monocultures. Food production was underrated and the government favored an export-oriented economic model[1,2]. Most of the domestic food requirements were therefore covered by imports[3]. The strong relationships with the Eastern European countries and the Soviet Union strengthened Cuba's green revolution model. However, the ecological, economic and social problems associated with this model led to increased unsustainability and vulnerability of Cuba's agricultural system[4].

The loss of the most important markets after the collapse affected Cuba's ability to purchase agricultural inputs such as agrochemicals, petrol, machinery and spare parts. Thus, the agricultural sector struggled to maintain its productivity[5]. Compared to the input availability before the crisis, the imports of agrochemicals dropped by 80%, diesel imports fell by 47% and petrol by 75% within a period of 2–4 years after the collapse. Furthermore, food imports were cut by half[6]. As a result of the resource shortages, Cuba's economy suffered from a decline in agricultural production that brought the island to the

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brink of a food crisis—with alarming impacts on human health. In addition, the United States trade embargo exacerbated the situation[7].

Adaptation strategies by the Cuban government

Cuba's government implemented economic austerity measures and emergency changes to face the crisis. The strategy included a new domestic economic policy, allowing foreign investments, liberalization of the dollar and granting licenses for private work in different sectors[8]. Structural changes and adjustments also influenced Cuba's agriculture since 1990[9].

Cuba's recent history has been shaped by steady changes that have influenced economic and social life of the citizens. The Cuban government enabled access to fallow land in usufruct in the early days of the crisis to boost food production. Then, in 2008 the government decided to facilitate even more the access to land and called for willing people to produce food[10]. In 2011, the Cuban Communist Party adopted a resolution that included 313 measures to improve the country's economy. One of most remarkable measures, with considerable impact on society, was the granting of licenses for self-employed work. For the agriculture sector, the measures included further strategies to reduce fallow land, to increase agricultural productivity, to reduce imports and to prioritize domestic food production, with the aim of achieving a higher degree of self-sufficiency[11].

Through all these adaptation strategies Cuba's decision-makers managed to overcome the worst of the crisis. Food production was stimulated by initiating a nationwide transition towards a sustainable agricultural model based on the principles of agroecology[11–14]. Sustainable agriculture refers to the development of multifunctional agro-ecosystems that take advantage of the integration of plant and animal biodiversity. The aim is to enhance biological efficiency, to maintain agro-ecosystem productivity and its self-regulating capacity[15]. Besides food and non-food products for peasants' families and markets, sustainable agriculture also provides public goods such as clean water, biodiversity conservation and soil fertility[16]. The shift towards agricultural sustainability is an evolutionary process depending on political, economic and social conditions[17].

The Cuban government facilitated location-specific production strategies, participatory research and extension approaches, institutional decentralization, the promotion of organic and locally available inputs, more localized production–consumption networks and the development of the urban agriculture movement[3,4,18]. Emphasis was also put on diversification of agriculture and markets, downsizing large state farms, increasing post-harvest efficiency, raising farm gate prices and improving rural conditions to avoid depopulation of rural areas. State subsidies for agriculture dropped between 50 and 90% from 1990 to 1996. The government reduced direct control over food production and distribution, and encouraged local initiatives and activities at grassroots level[5].

Experiments with integrated pest management, biological pest control, vermiculture, farm diversification, cover cropping, intercropping and other agroecological practices became successful strategies to avert grave shortages in food supplies[19]. Through input substitution and more efficient use of local resources, Cuba has reached a high degree of agricultural sustainability[2,4,19–22]. Organizational changes in the structure of the agricultural sector resulted in a new land-tenure distribution. Many state farms were split into smaller production units. Land tenure was divided into the state and the non-state sectors. The non-state sector included individual agricultural producers with private or usufruct land-tenure, private cooperatives and collective farms with usufruct tenure[7].

The role of farmers in mitigating the crisis

The changes initiated by the state or by a lack of choice focused on technologies and practices based on local knowledge, skills and resources[5]. Small farmers, who privately owned their land, showed high adaptability to the challenges emerging from resource scarcity during the crisis. They never abandoned traditional practices such as crop rotation, intercropping or seed conservation. In certain regions of the country oxen have always been used for animal traction despite high levels of mechanization in the rest of the island. These peasants became crucial resources for national training programs. Their local knowledge of traditional practices was a key element in adaptation to the new circumstances[5,21]. Private farmers played a major role in the transition process towards more agricultural sustainability as their farming model was aimed more at local and diversified production than large state farms. They had greater control of farm management and were less dependent on external inputs[2]. Also citizens without practical experience in agriculture started to produce food—they either entered the urban agriculture movement or moved to the countryside. Many of the new food producers were well educated and some even held university degrees[8].

Over the past 20 years Cuba's economic situation has gradually improved but the US trade embargo still affects resource availability. Thus, sustainable agriculture based on low external inputs remains an important strategy for Cuban food production[19]. Today, Cuba's agriculture is far removed from high levels of agrochemical inputs. Peasant farming is characterized by a relatively small farm size, mixed farming systems, polyculture, crop rotation, animal traction, family labor, local distribution of products and minimal use of off-farm resources. Thus, peasant farming in Cuba draws close to low external input sustainable agriculture (LEISA). Although an increasing number of farmers experiment with sustainable

practices and technologies[13], export-oriented agriculture is still based on chemical inputs and only a few domestic products would meet organic certification standards. Furthermore, farmers' commitment to agroecology should not be taken for granted[5,12].

Defining farmers' experiments

An experiment is 'the action of trying anything, or putting it to proof; a test, trial; an expedient or remedy to be tried; a tentative procedure'[23]. Farmers' experiments are activities that involve close observation. These activities are often triggered by changing circumstances and opportunities. In their experiments, many farmers want to prove something to others or want to check what others say. Experimenting is also understood as comparison of something known to something unknown[24,25]. It means to come up with something new and then to implement it and try it[26]. Experiments and innovations are different but complementary concepts[27]. Experimenting can be seen as the process, by which an innovation is generated, tested and/or evaluated[28–30]. Thus, farmers' experiments refer to informal trials or tests that potentially result in innovations[31]. An innovation is 'an idea, practice, or object that is perceived as new by an individual or other unit of adoption'. It matters little whether or not the innovation is objectively new. The perceived newness for the individual determines the innovative character of the idea, practice or object[32].

By experimenting, farmers generate or discover new knowledge and combine it with already existing local knowledge[33]. Farmers' experiments and innovations have been part of agriculture for thousands of years and were important means through which advances in agriculture were made[34]. Testing new methods and technologies has been an integral element of farmers' daily working routine[30,35–38]. The history of agriculture has been characterized by frequent changes at the biophysical, agroecological, socio-economic, socio-cultural and political levels. Farmers have faced an array of changing contexts that required adaptation processes[39]. In such a dynamic scenario, experimenting is an important strategy in order to adapt farming systems to changing conditions.

The process of experimenting

Changing conditions challenge farmers and may trigger adaptation strategies. Experimenting often aims at improving the current situation[40]. Farmers contrast and combine local knowledge with new ideas. Their own ideas are important sources for experiments but extension agents, scientists or other farmers also introduce ideas that trigger experiments[29,30,37,41].

The motives to initiate an experiment are as diverse as the topics themselves. Economic considerations, improving pest control, reducing work load or increasing self-sufficiency motivate farmers to experiment[34,37,42]. Personal motives and environmental considerations also drive farmers' decisions to experiment[27,36,43].

Experiments are mainly based on locally available, physical and biological resources, such as local seeds, manure or labor[30]. Most of the farmers' experiments are technical but some experiments also deal with economic, social and institutional issues. Common technical topics are related to new crops or varieties, soil preparation and fertility, sowing methods and crop density[31,44].

Experiments vary from very easy to very complex[27]. The farmers' research process involves the experimental design, monitoring processes and the assessment of results[30]. Farmers usually conduct their experiments on small plots and try to maintain them on a simple level to reduce the risk of failure[45]. They rarely have a fixed anticipation of the outcomes straight from the beginning, and according to the course of the experiment they decide whether to continue, stop[46] or modify the ongoing experiment.

Continuous observation is the most common and practical way to evaluate an experiment. Farmers are usually self-critical when evaluating their experiments as they rarely benefit from whitewashing their results[45].

Farmers' experiments can either result in hard or soft innovations. Hard innovations are physical and visible, such as tools, irrigation systems, crops, substances for pest control and so on. Soft innovations are intangible such as new knowledge, communication strategies or marketing attempts[47].

Institutional context of farmers' experiments in Cuba

Farmers' experiments in Cuba are embedded in a specific and influential institutional context. The National Small Farmers' Association (ANAP) plays an important role in the widespread dissemination of agroecological practices through farmer-to-farmer extension. The association represents smallholders' interests to the government. ANAP is a member of the transnational peasant movement La Vía Campesina. In 1997, the association decided to implement the farmer-to-farmer methodology, which had already been in use in other Latin American countries[13]. The Agroecological Movement Farmer-to-Farmer (MACAC) has been attractive to farmers: more than 110,000 rural households belong to the movement and apply agroecological practices to manage their farming systems. Farmers' experiments and exchange of experiences using the farmer-to-farmer methodology are key elements of the movement[48].

The Programme for Local Agricultural Innovation (PIAL) that was implemented by the National Institute of Agricultural Sciences (INCA) also supports sustainable agriculture practices in Cuba. The program has its origin in a participatory plant-breeding project that started in 2000. Environmental issues have been a permanent element throughout the project. PIAL promotes the design, construction, implementation and evaluation

of local agricultural technologies. Staff members encourage peasants to experiment and to become the main protagonists of local agricultural innovation processes. Knowledge exchange among farmers and between farmers and scientists during workshops and innovation or biodiversity fairs facilitate mutual learning[46,49]. In 2010 around 50,000 farmers participated in the PIAL project[50].

Contextual framework for studying farmers' experiments

The structural changes in Cuba's agricultural sector since 1990 and the nationwide, large-scale experiment with sustainable agriculture[2,3,8] built the contextual framework for this paper. The break-up of trade relations with former socialist countries in Eastern Europe triggered coping strategies by the government and by private persons. To overcome the worst of the emerging food crisis, Cuban farmers have become innovative and farmers' experiments have been an indispensable element for adapting to the changing conditions. In such a context, farmers' capacity to experiment represented an essential precondition for the conversion to sustainable agriculture[51]. Farmers' experiments are still an integral part of Cuba's agriculture and constitute farmers' means of dealing with the multiple challenges emerging from food production[52]. However, detailed descriptions of farmers' experimental processes are scarce. This raises the question of how farmers actually experiment to achieve applicable outcomes. To answer this question, we examine the topics, resources, sources, motives, methods, outcomes and the dissemination of farmers' experiments in Cuba. Based on our findings, we discuss the significance of Cuban farmers' experiments and their potential contribution to adapting to changing conditions.

Methods

Field research in Cuba was carried out in 2007 and 2008. In each year, 5 months of field research were conducted with a student's visa under an official agreement between the University of Natural Resources and Life Sciences, Vienna (BOKU), the Experimental Station 'Indio Hatuey' (EEIH) and the National Institute of Agricultural Sciences (INCA).

The municipalities selected for field research differed in topography, climate and agricultural structure. In addition, La Palma, a municipality in Pinar del Rio, was selected due to its participation in the PIAL program. In Sancti Spiritus province, various municipalities were chosen because of the active and widespread farmers' participation in the MACAC. Field research was also carried out in the municipality of Baracoa in Guantanamo, where the Swiss Research Institute of Organic Agriculture (FiBL) promoted certified organic farming for export. Interviews were also conducted in the provinces of Matanzas and Havana with rural farmers and urban producers, due to recommendations of the research counterparts.

Interviews with farmers were carried out with official authorization. Informants were selected through a purposeful sampling combined with a snowball sampling[53]. Pre-tested semi-structured interview guides were used and complemented by informal and unstructured interviews in situations where semi-structured interviews were not feasible. The interviews were conducted face to face at the respondents' farms with 72 male and female farmers during up to two visits per farm.

Living in the study area and working with farmers as key informants[54] facilitated additional insights into farmers' perceptions of their own experimental activities and deepened the understanding of farmers' experiments. Participant observation was realized when working with farmers, at farmers' workshops, cooperative meetings, scientific and semi-scientific conferences, innovation award forums and university courses. Selected relevant phases were digitally recorded. Field notes were written during participant observation and when working with farmers. A research diary was kept to document and reflect on the research process. Expert interviews were conducted to obtain additional insights into the situation of organic farming, farmers' experiments and innovations, and the knowledge and communication network in Cuba. Secondary data such as articles in local newspapers, manuals and leaflets of development projects, documents of the Cuban innovation award forum and other relevant media were used to contextualize farmers' experiments and innovations within society[55].

Most interviews were recorded with a digital voice recorder and transcribed in original Spanish with the software Express Scribe. Transcripts were coded thematically and analyzed with the software Atlas.ti using a combination of content analysis and grounded theory based on deductive and inductive coding[56]. According to the research questions, thematic categories were defined and formed the basis for the coding process. Data were categorized into descriptive and thematic code families. Some of these families were based on the research questions, whereas others emerged from comparing and contrasting similarities and differences in the interview data[55]. In addition to the coding procedure, analytic memos were written to narrow down information from data. Memoing was done to keep track of relevant ideas concerning the research theory and its connection to codes. Operational memos were used to reflect on practical matters during the research process. The next step was a quantitative analysis of qualitative data. This involved turning written text into numbers. Profile matrices were elaborated for thematic code families to examine the number of occurring codes. Finally, univariate analysis was carried out to elaborate frequency distributions of the attributes relevant to assess the experimental process[53].

Results

Farmers' definition of experiments

With the term 'experiment' Cuban farmers associated informal or formal trials on their farm. The terms respondents used most often when talking about an experiment were: trying, searching, observing, inventing, proving, experimenting and knowing. To these farmers experimenting meant trying something new at farm level and learning from the results. It was seen as a way to search for solutions of farm-specific problems. Observation formed an integral part of the experimental process and contributed to increase experience. Through experimenting, interviewees tried to remove doubts by proving or disproving what others say or recommend.

Topics of farmers' experiments

Respondents mentioned a total of 370 farmers' experiments (Fig. 1). Upon the first authors' request, each respondent explained at least one experiment in detail except one female farmer who did not mention any experiment. A respondent who was experimenting very actively mentioned 32 different experiments.

The majority of the experiments were related to the introduction of new crops or varieties. Most of the introduced crops were common in the respective area and respondents benefitted from the experiences of neighboring farmers and general knowledge in the region. Only a few interviewees experimented with special crops that were unusual in the region (e.g., cinnamon (*Cinnamomum verum*), anis (*Pimpinella anisum*), ginger (*Zingiber officinale*), potato (*Solanum tuberosum*), napa cabbage (*Brassica rapa* subsp. *Pekinensis*) and broccoli (*Brassica oleracea* var. *italica*)). They mostly received the seeds for free and planted them on a small scale, avoiding financial risk. Additionally, INCA encouraged farmers participating in the PIAL program to test different varieties to identify the most suitable for the local conditions. The respondents experimented to increase yields, avoid pests and diseases, and identify the varieties that were best suited for cooking and tasted better than the traditional ones. One respondent mentioned that she cultivated 106 different bean varieties. Another farmer enjoyed planting cassava varieties and was proud of the 44 different varieties he was cultivating on his farm.

Experiments related to plant production included variation in sowing dates, and distances, trying new sowing methods, different ways of crop rotation, grafting, trying different harvesting methods and dates, as well as different forms of seed conservation. Four farmers experimented with plant nurseries. Some of the interviewees who participated in PIAL were engaged in plant-breeding activities and even developed new varieties of beans or maize. One respondent explained that she put a plastic bag around the bunch of bananas to shorten the ripening time. Another respondent used biogas for seed conservation.

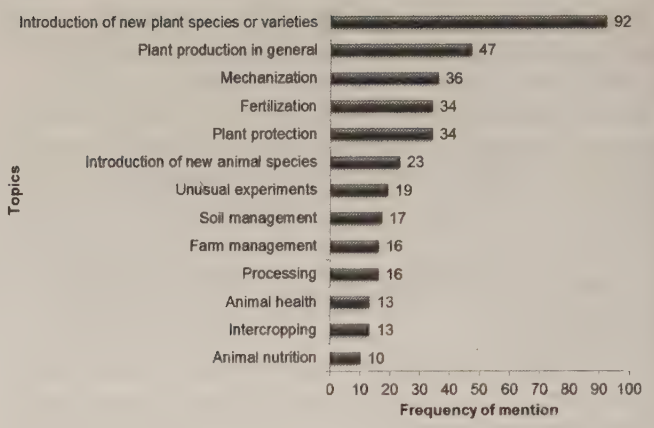

Figure 1. Topics of farmers' experiments in Cuba ($n=72$; frequency of mention; multiple answers per respondent possible).

An urban producer experimented with *Trichoderma* sp. to improve plant vitality.

Mechanization, as another subject, included experiments with tools, machinery and other farm equipment. Farmers either recreated or modified already existing tools. In a few cases, the respondents invented new machinery such as a multi-plough with 28 different uses, an irrigation programming system that runs without electricity or fossil energy, or a sowing tool built from recycled material. Other experiments related to farm equipment included the construction of mills, wells, a drier or a disc plough. Tools that were developed through experimentation included rakes, crowbars or harvesting tools. Mechanization also referred to simple innovations that made daily work easier. One respondent perforated a small plastic medicine tin to reduce plant damage when irrigating.

Organic fertilization was a frequent concern of many farmers. Thus, many respondents experimented with compost making, vermicompost, worm humus tea, green manure or manure from bats or chicken. Elaboration of vermicompost was also promoted by MACAC and the urban agriculture movement. Apart from the elaboration of different compost types, respondents experimented with the application of organic fertilizers on different crops.

Experiments related to plant protection included the elaboration and application of natural insecticides such as neem (*Azadirachta indica*) and tobacco (*Nicotiana tabacum*) or mechanical treatments such as boiling water against ants. Coconut palms (*Cocos nucifera*) were occasionally infested by the coconut mite (*Aceria guerreronis*) and respondents tried to eliminate the mites by burning infested material or by pealing the trunk in the form of a ring. Other experiments for pest control were sowing repellent plants, setting up traps with attracting colors or other baits. One respondent applied grease on the borders of a raised bed to prevent snails and bugs from entering the plot.

By introducing new animal species on the farm, respondents gathered first experiences with unfamiliar tasks. They were hardly aware of the experimental character of the undertaking. One interviewee experimented with free-range pig keeping because he wanted his animals to plough the soil. Women were often responsible for small animal breeding such as chicken, turkeys or rabbits. Three female respondents mentioned that they tried to put the eggs of another chicken breed, of guinea fowls or pheasants into chicken nests to let the chicken hatch the eggs.

Unusual experiments referred to agronomic trials that did not fit into any other category because of their extraordinary character. Such experiments included the elaboration and application of effective micro-organisms, the use of magnetized water, testing the influence of the lunar cycle, or trials with pyramidal energy to improve seed quality. One farmer realized several experiments on the feeding of effective micro-organisms to pigs and rabbits, and presented his findings in scientific and semi-scientific conferences. Experiments related to the lunar cycle involved planting or harvesting, making cuttings and neutering boars or bulls according to the moon. Other experiments in this category were the precise and daily documentation of weather conditions, establishing an outdoor meeting place for workshops, and introducing a so-called idea meeting where farm workers were encouraged to present their plans for the coming year.

Farmers' experiments that affected a whole farming system were the introduction of a new activity such as establishing raised beds for organic vegetable production (*organoponico*) or starting with livestock-keeping, introducing fixed rotational grazing pastures or digging a drainage system. These undertakings often included a series of interrelated experiments to gather experience. Construction of farm infrastructure, such as buildings or fences, also included experimental steps, especially when resources became scarce. The search for the best growing site on a farm for a specific crop also affected the whole farm and led to changes in farm segmentation.

Experiments related to soil management referred to different tillage methods or the introduction of living or non-living barriers to avoid erosion. One respondent tried to improve the fertility of his sandy soils by applying organic matter. Over time, he was able to grow a greater variety of plants.

Experiments to process farming products were prevalent in urban agriculture and among female farmers. These experiments included wine production, clearing up wine, producing vinegar, sauces and fruit juices or fruit pulps.

Respondents who faced animal health problems had to search for alternative treatments due to a lack of purchasing opportunities. Experiments to maintain animal health included the use of natural medicine such as mamey (*Pouteria sapota*) for superficial application or cilantro (*Coriandrum sativum*) for internal use. One respondent, a veterinarian, mentioned four experiments with natural substances to eliminate parasites.

Intercropping was a way to make the most out of the space available. Some combinations worked out well, while others did not. Most respondents tried combinations that were generally known among local farmers, such as maize and beans. Some respondents experimented with unusual combinations such as sunflower and cucumber.

Experiments with animal nutrition aimed at optimizing the daily feed rations or using locally available resources for feeding. One respondent tried to feed pineapple skins to chicken, while another farmer experimented to identify the optimal amount of coconut flakes in rabbit fodder without increasing the risk of heart attacks caused by too much fat. Another respondent separated a group of pigs and fed them with additional soybean in the fodder ration. After 45 days, he concluded that the pigs fed with additional soybean fodder ration increased more in weight than pigs without soya feeding.

Resources for farmers' experiments

Farmers relied on physical and non-physical inputs to conduct experiments and develop innovations. Physical inputs involved materials such as seeds or wood and the tools necessary to perform the experiment. Non-physical inputs were knowledge, time and labor. Resource scarcity determined the materials and tools used during the experimental process. Searching for inputs was often a precondition for experimenting. Just a few respondents had all the resources required for the experimental process. Participation in a development project, such as PIAL or MACAC, facilitated the farmers' access to resources.

Lack of resources (e.g., tools, material or money) often required the use of recycled material. Most of the interviewees were frequently searching for secondary uses of bottles, tubes, cans or other devices. However, discarded material seldom exactly matched their specific needs, thus farmers had to be creative when implementing the available resources.

Most of the experiments in the sample were based on physical inputs, such as seeds, plants, animals, wood, cans, plastic bottles, plastic bags, iron, wire, engines or barrels. For social experiments, such as testing the feasibility of a farmers' meeting for the exchange of ideas, or for methodological experiments, such as new ways for the assessment of pest damage, farmers needed non-physical inputs, for example knowledge.

With the anticipated experiment in mind, the respondents often started thinking about the required material. In most of the cases (74%), the first step in the search for material was to check the resources available on the farm. The rest began to search for material outside the farm. In total 64% of the respondents claimed to combine on-farm and off-farm material when experimenting. The rest

used either material from the farm or from outside. Communication skills and personal contacts, persistence and also luck facilitated the farmers' search for discarded material. More than half of the respondents (54%) used discarded materials for experimenting. The rest either relied on locally available plant material and seeds or had to purchase the required inputs.

Experiments in crop production required plant material. Respondents derived seeds and seedlings for experimentation, e.g., from propagating their own crops, or they received the material from other farmers, from the agricultural state enterprise or from research entities; the plants were given as a gift or had to be purchased. Other experiments (e.g., the use of a natural insecticide) were based on wild plants or plants that grew on the farm anyway.

Those farmers who participated in a development project, especially, dedicated certain plots exclusively for experimentation. However, others who experimented with new plants or varieties also devoted farmland to experimentation. Respondents usually conducted their experiments on their own farm. Just 4% of the interviewees experimented partly outside their farms when working with special machinery or tools.

Information was an important element and resource before or during the experiment. The majority of the respondents (83%) claimed that they actively searched for or received information. The most important sources of information were other farmers, extension workers or scientists. Farmers with access to technical literature actively searched in books or magazines for information about the topic of the experiment. In cases such as the construction of a specific tool or machine, farmers consulted professional experts, for example craftsmen, carpenters or blacksmiths. Those respondents who expressed not having used external information claimed that they were the experts on the topic of the experiment. These experiments were based on the farmers' own ideas, intuition and local knowledge. Occasionally, farmers drew on knowledge from their childhood, knowledge gathered during education or information from TV, radio or written texts.

Labor was a key input for performing experiments. Respondents worked alone in cases where the experiment was easily manageable (Fig. 2). However, the more complex the experiment and the higher the workload, the bigger was the respondents' need for help. Family members were the main assistants in the experiments. They were most often present when the respondent experimented and therefore could give valuable feedback. Occasionally respondents received help from farm workers, craftsmen, extension agents or scientists, other farmers, neighbors and friends.

Limited availability of technical equipment for experimenting increased the farmers' demands for specialized external labor. Blacksmiths or carpenters had special facilities, machinery or tools at their disposal and, in addition, could provide expertise. Work orders included construction of specific spare parts for tools or machinery, welding of metal or woodwork.

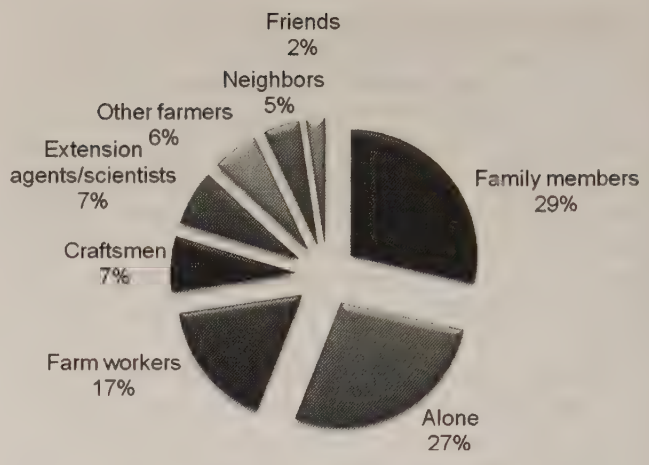

Figure 2. Distribution of the workload during farmers' experiments ($n=72$; 100% = total of all answers given by the respondents on people contributing with labor to the farmers' experiments).

Farmers willing to participate in an innovation award forum or a conference frequently asked for help to prepare a written document about the experiment, scientific or semi-scientific posters and computer presentations. In these cases, local extension agents, office assistants from the farming cooperative, scientific staff members or family members with access to computers helped out.

The time required for conducting an experiment depended strongly on the topic, the commitment to the experiment, its complexity, the motivation and the need to finish. In most cases initial considerations and reflection processes led the way to experimentation. However, respondents also mentioned spontaneous experiments.

Farmers either experimented in their spare time or during their daily working routine. Agricultural production had priority over spending time on experiments with uncertain outcomes. Thus, farmers' experiments were more likely a side activity of agricultural production. Higher commitment increased their willingness to spend additional time and effort to achieve satisfying outcomes. Interviewees who were actively involved in a participatory research project spent more time setting up and evaluating the experiments than most of the other farmers. Respondents who aimed at presenting their results to a wider audience spent additional time on documentation.

Time input also depended on the need to obtain applicable results. Under certain circumstances, respondents required immediate results. Experiments with very short time requirements indicated improvised solutions for suddenly occurring problems, e.g., a broken tool. These solutions met short-term demands and occasionally lasted for a long period of time, such as the construction of

a ditch to avoid fodder losses during heavy rainfalls. In comparison, the establishment of integrated-farming systems was accompanied by continuous and selective experimentation and could last for years to reach the desired outcomes. Respondents who experimented with permanent crops could only assess the results after some years. The construction or modification of tools or machinery required material that occasionally was difficult to obtain. The construction took little time compared to the time necessary to find the material. One respondent searched for the material to build a disc plough for half a year. After compiling a variety of different recycled materials he started to experiment by creatively putting together the useful items and finished the disc plough within one day.

Most respondents required tools and equipment for experimenting. The topic and the complexity of the experiment determined the tools needed. Standard farm inventory, such as a machete, hoe or crowbar, was most frequently used during experimentation. Farmers who were engaged in the construction of agricultural machinery, such as sowing machines or ploughs, had to use special tools. Research-minded farmers sometimes owned these tools but they mostly belonged to craftsmen. Occasionally, respondents made recourse to machinery of the farming cooperative, for example when building a pond or when incorporating green manure. Farmers who conducted scientific or semi-scientific experiments with the aim of participating at an innovation award forum or at a conference required calculators, digital cameras or computers for analysis. Only few farmers owned the necessary equipment. They had to borrow the equipment from friends or relatives, or they asked extension agents for help. In contrast, some respondents even got along without any tools, such as one breeding experiment with chickens.

Only 16% of the respondents required money to conduct their experiments. Money was necessary to purchase-specific inputs, for services of craftsmen or to pay farm workers. If experimentation was done during working time, some respondents mentioned a loss of income because of experimenting.

Sources of ideas for experimenting

The ideas for experiments often had multiple sources. They were either based on the respondents' own ideas or on a combination with external sources (Fig. 3). Most of the interviewees (58%) claimed that it was their own idea to start a specific experiment. However, external information often influenced decision-making before or during the experimental process. Some respondents reported that the experiences of previous experiments or innovations triggered new experiments. Others expressed that their idea was influenced by experiences they had in their childhood. Two farmers mentioned that the idea to start experimenting was a result of coincidence. Unswayable

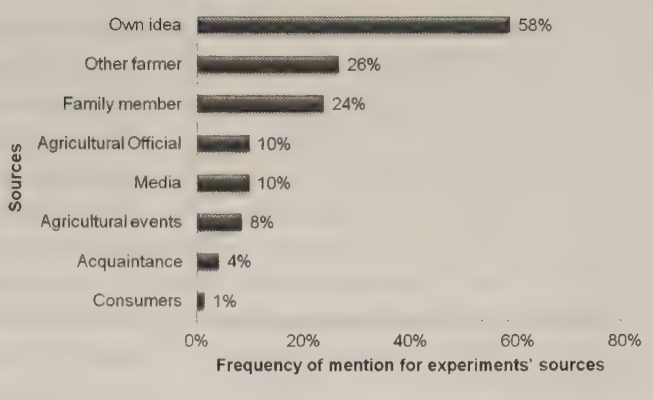

Figure 3. Sources of farmers' experiments ($n=72$; 100% = the total of all answers given by the respondents; multiple answers possible).

circumstances at farm level triggered the farmers' decisions to take further action. One respondent mentioned the lack of resources that triggered the experimental process.

Opportunities to meet other farmers favored knowledge exchange and appropriation, and were crucial for gathering new ideas about potential experiments. Neighboring farmers usually shared similar knowledge, culture and social status with the respondent. Thus, knowledge transfer was characterized by mutual trust about agricultural experiences. However, some respondents also questioned statements or recommendations of others and tried to gather their own experiences.

Family members played an important role in decision making and frequently provided ideas for experiments. The generation gap between family members in two cases (planting distance of coco palms; planting sweet potatoes according to the lunar cycle) prompted experiments that were conducted to rebut the opinion of the elder. In these cases, finally, the respondents had to accept that the experiences of their elders were trustworthy.

Most respondents mentioned regular contact with agricultural officials affiliated to farmers' associations, research institutes or agricultural enterprises. These officials enjoyed a high level of credibility and were the impetus for several experiments.

Especially respondents with higher education or research-minded farmers mentioned media as a source for their experiments, whereby books and brochures were the most important media. Just one respondent mentioned the internet as a source for his experiment.

Agricultural events such as fieldtrips, workshops and scientific or semi-scientific events provided new insights and ideas for some of the respondents. Especially, respondents who participated in MACAC or PIAL gathered ideas during related events.

In three cases acquaintances and friends without a farming background gave the respondents the idea to experiment. One respondent mentioned consumer demands as a source.

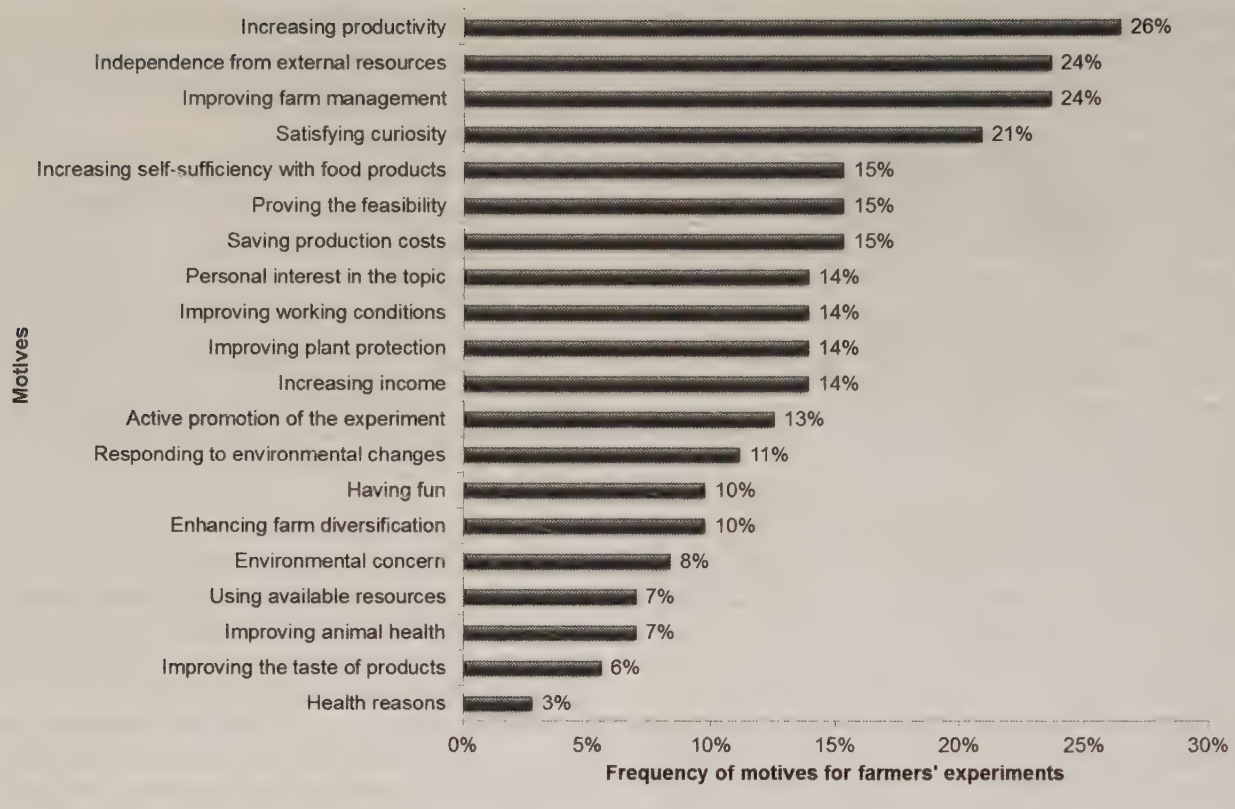
Increasing productivity 26%
Independence from external resources 24%
Improving farm management 24%
Satisfying curiosity 21%
Increasing self-sufficiency with food products 15%
Proving the feasibility 15%
Saving production costs 15%
Personal interest in the topic 14%
Improving working conditions 14%
Improving plant protection 14%
Increasing income 14%
Active promotion of the experiment 13%
Responding to environmental changes 11%
Having fun 10%
Enhancing farm diversification 10%
Environmental concern 8%
Using available resources 7%
Improving animal health 7%
Improving the taste of products 6%
Health reasons 3%
Motives
0% 5% 10% 15% 20% 25% 30%
Frequency of motives for farmers' experiments

Figure 4. The frequency of mentioned motives for farmers' experiments ($n=72$; 100% = the total of all answers given by the respondents; multiple answers possible).

Motives for experimenting

Most respondents mentioned various motives for one single experiment. The most important motive to start experimenting was to increase agricultural productivity (Fig. 4). Respondents tried to increase productivity either by introducing new crops or animals, by searching for better-adapted varieties to achieve higher yields, by intensification of crop production or by introducing or diversifying elaborated products. Experiments with agricultural facilities such as irrigation, drainage, sowing tools or ploughs finally also resulted in higher productivity.

Reducing dependency from external resources was mentioned by several interviewees, mainly because of limited access to these resources or high prices of farm inputs. Curiosity was another important driving force for experimentation. Respondents claimed that they started to experiment because they wanted to know how the experiment performed and what the outcomes would look like. Improving farm management referred to specific farming situations that required the farmers' attention and called for improvement.

Increasing self-sufficiency of food products was often related to cost reduction or the wish to diversify the diet. Some agricultural products were hardly available on the official farmers' markets. Thus, farmers chose to produce them themselves when they had the chance to obtain seeds. Gathering their own experiences from experimenting was crucial for the respondents who tried to assess the validity of external information. Some interviewees wanted to oppose the opinion of relatives, other farmers or extension workers and experimented to prove that a certain technology or farming practice was viable. Others experimented to demonstrate the applicability of a technology or practice they were convinced of. Some respondents mentioned that they enjoyed farming and claimed that trying new plants was an integral part of agriculture.

Improving working conditions included facilitating work, reducing working time and improving occupational safety. Problems with pests or diseases triggered experiments to find better ways for plant protection. Farmers tried to improve their economic situation by experimenting with promising alternatives.

Occasionally other farmers, extension agents or scientists actively promoted experiments with new technologies or practices. Active promotion of an experiment mostly complemented the respondents' own motives. Some respondents claimed that environmental changes (e.g., irregular precipitation, heavy rainfall, droughts and floods) motivated them to experiment because they wanted to maintain a productive system.

Some farmers stressed their commitment and the gratification they received from farming. These respondents were enthusiastic experimenters and enjoyed trying out new things. Some respondents expressed that they

started to experiment because they realized that diversified farming systems were more resilient. Their motive was to diversify the agroecological systems to be prepared for changes.

Some respondents held a deep understanding of environmental interactions and mentioned that environmental concerns motivated them to experiment with sustainable agricultural practices. Making the most of locally available resources was also a motive for experimentation. Ensuring animal health was a motive for those who had to treat animals when injured or ill. Some farmers wanted to improve the taste of agricultural products. A few interviewees also mentioned that health reasons triggered their experiments.

Methods applied by experimenting farmers

Respondents hardly worked according to a fixed agenda or rigid methods. Moreover, when repeating an experiment in the field, environmental conditions probably changed. Thus, adaptation of the applied methods was essential to improve the experiment. Continuous reflection on the performance of the experiment was important to adapt the methods and to achieve applicable outcomes. About one-third of the respondents adapted the methods during the course of the experiment.

Expectations. Before starting to experiment, respondents potentially developed expectations of the outcomes. High resource input usually meant higher risk of financial losses. Thus, confidence to succeed was more important for input-intensive experiments. If experimenting required few inputs, there was little to lose and respondents even experimented with negative expectations. These expectations were influenced by previous experiences or indications from other persons. Most respondents (68%) were convinced or hoped that the experiment would finally lead to applicable results. Some respondents (26%) just wanted to see if the experiment was feasible, positive or negative expectations were missing. A few respondents (6%) had negative expectations and believed that the experiment would fail. Most of these respondents wanted to disprove statements of others.

Planning. More than the half of all respondents (58%) started without having a detailed written or mental plan in advance but made some basic considerations about the experiment before starting. They specified their plan step by step. Few respondents (4%) experimented spontaneously without any plan. Thirty-eight percent of the experimenting farmers elaborated a concrete plan before they started. They balanced the pros and cons of initiating the experiment, reflected upon the appropriate approach and anticipated the steps necessary to achieve applicable results. Some of these respondents produced a written document (6%), a draft (6%) or a model (4%) before starting to experiment. Respondents stated that having a draft helped them to anticipate the desired outcomes, and building a model enhanced their imagination and made the idea more tangible. Four percent of the respondents relied on a written document or a draft elaborated by extension agents or scientists. Some respondents who conducted scientific and semi-scientific experiments claimed to use random sampling. One respondent conducted an experiment with *crotalaria* as green manure and measured the biomass production during 5 years. Every year he took various randomly selected samplings of one square meter from a one-hectare field. He explained that he entered the field and spontaneously chose the areas for the sampling. Another farmer, a former employee of a plant protection institute, experimented with four different salad varieties to assess yield differences. He cooperated with a scientist from an agricultural research institute who provided seeds and occasionally technical advice. However, the farmer himself elaborated the experimental design and realized the experiment. He set up four repetitions of each variety and took randomly selected samplings of one square meter from each variety to assess yield differences.

Scale. Starting on a small scale, with few plants or animals, was a way to minimize risks and to gather first experiences for most of the respondents (90%). Respondents built on the experiences they gathered and, if necessary, adapted the experiment accordingly. Finally, they applied the results on a larger scale, proceeded on a small scale, or rejected the findings. Step-by-step experimentation (8%) mostly concerned technical experiments. During technical experiments, respondents tinkered with the item and evaluated the intermediary outcomes.

Farmers started an experiment on a large scale (10%) when they were convinced that the experiment would succeed and estimated that little risk was involved in the undertaking. If the information source was trustworthy and respondents confided in the feasibility of the experiment, they dared to start on a large scale. Starting on a large scale also depended on the selling value of the potential outcomes. Economic dependency on the outcomes led to increased precaution and lowered their willingness to start using large-scale experiments. Furthermore, starting on a large scale depended on the topic of the experiment.

Observation. Direct observation was the most important instrument to assess the performance and the outcomes of the experiment and to gather experience. Eighty-nine percent of the interviewees used observation to draw a conclusion. Several respondents claimed that attentive observation was a farmer's most effective tool to analyze experiments. Most experiments were embedded in working routine, and daily observation was part of it. Some respondents (11%) also conducted systematic observations. They checked the performance of the experiment regularly and kept specific parameters under review. Other experiments just allowed observation of the final results, such as transplanting root vegetables, or observation at an advanced moment of the experiment, as in the case of the transplanting distance of coconuts. Several

years after transplanting, the farmer could say that the distance was too short and concluded the negative effects of his experiment. Observation of technical experiments differed from cropping or livestock experiments and required step-by-step improvement and adaptations.

Comparison was another effective way to assess the performance and the outcomes of an experiment. Most respondents (60%) made direct comparisons with the traditional production on their own farm or with the outcomes of other farmers. The rest of the respondents conducted experiments without comparison.

Repetitions. Repetition of farmers' experiments referred to repeating the same or a modified version of the experiment at a subsequent date. Few farmers set up scientific experiments with repetitions of the same treatment at the same time but on different plots. Repetitions were often complementary to direct comparison. Almost half of the respondents (49%) repeated the experiment at least once until it was converted into a regular farming practice. One farmer experimented with effective micro-organisms. In the first experiment he treated young rabbits. Then he conducted the same experiment but with adult animals. One respondent claimed that he repeated the experiment of planting two sprouts of yucca instead of one. In the first year he tried it on a slope and the subsequent year he tried it on a level field and additionally he paid attention to the moon phase. This indicates that respondents modified parameters of experiments to improve the performance and still could be accurate about the validity of the outcomes. The construction or modification of farm equipment by itself was mostly a dynamic process of repeating the working steps in a different way until satisfying results were achieved.

Some respondents (13%) received hints from scientists or extension agents on how to conduct scientific experiments and repeated the same experiment on similar plots and at the same time. These farmers also achieved statistical results, which were valid for presentation at scientific and semi-scientific conferences. One respondent mentioned that he and his wife attended a lecture where they learned about experimental design. Scientific repetitions during one growing season were also done in an urban agriculture cooperative with academic staff responsible for experimentation or involved in participatory research projects.

Only a few respondents (6%) worked with control groups during their experiments. Experimenting was based on empirical experience, which influenced the evaluation of the experiments. Also without a control group, respondents were able to tell whether the results of an experiment were valuable or not.

Documentation. About three-quarters of the interviewed farmers confided in their memory and did not document their experiments. To their opinion, the benefits of writing down experiences hardly justified the efforts. In addition to observing and memorizing details of the experiment, some farmers considered written notes important for the experimental process. Twenty-six percent of the respondents claimed to take written notes. With increasing complexity of the experiment, documentation became more important. Respondents who participated in a development project took notes more frequently because of recommendations from scientists or extension agents. Respondents who wrote down their observations used note pads or notebooks. One respondent used the wooden wall of his house to document pig births. In participatory research projects, staff members systematically took notes of the experiment. Just a few farmers (7%) were able to document their experiment with photographs or using a video camera. Using private computers to document experiments was possible for very few farmers (4%).

In cases where production was delivered to the state procurement and delivery agency (*Acopio*), respondents measured their results quantitatively. Otherwise only farmers who conducted scientific or semi-scientific experiments measured parameters such as pest infestation, weight increase or yield per area. One respondent systematically measured the weight increase of rabbits every 10 days when applying effective micro-organisms. Two respondents were working on the same experiment about farmers' attitudes towards biological pest control and distributed questionnaires randomly. They analyzed the answers statistically.

Outcomes of farmers' experiments

Farmers categorized the outcomes of their experiments as being either positive or negative. Some experiments were still in progress and respondents could not yet assess the outcomes. The interviewees usually expected positive outcomes. Negative outcomes did not contribute to improve agricultural production and were therefore not applied. Nevertheless, negative outcomes increased the respondents' knowledge on the topic.

Furthermore, the interviewed farmers distinguished between innovations and inventions. They defined an innovation as something new on the farm that improved the situation, which means solving a problem by changing something to improve it and to achieve positive results. By innovating, farmers increased their experience about something new. However, an innovation might already exist but might be new to the farmer. An invention was defined as something 'absolutely new'.

Some respondents conducted experiments to prove or disprove a hypothesis. Other experiments happened incidentally and the farmer gathered unexpected experience as a side effect.

Outcomes were often context-specific and depended on the individual experiments. One single experiment could have various benefits for the farmer (Fig. 5).

Most interviewees mentioned improved productivity as an outcome of their experiments. Experiments that increased the degree of self-sufficiency represented

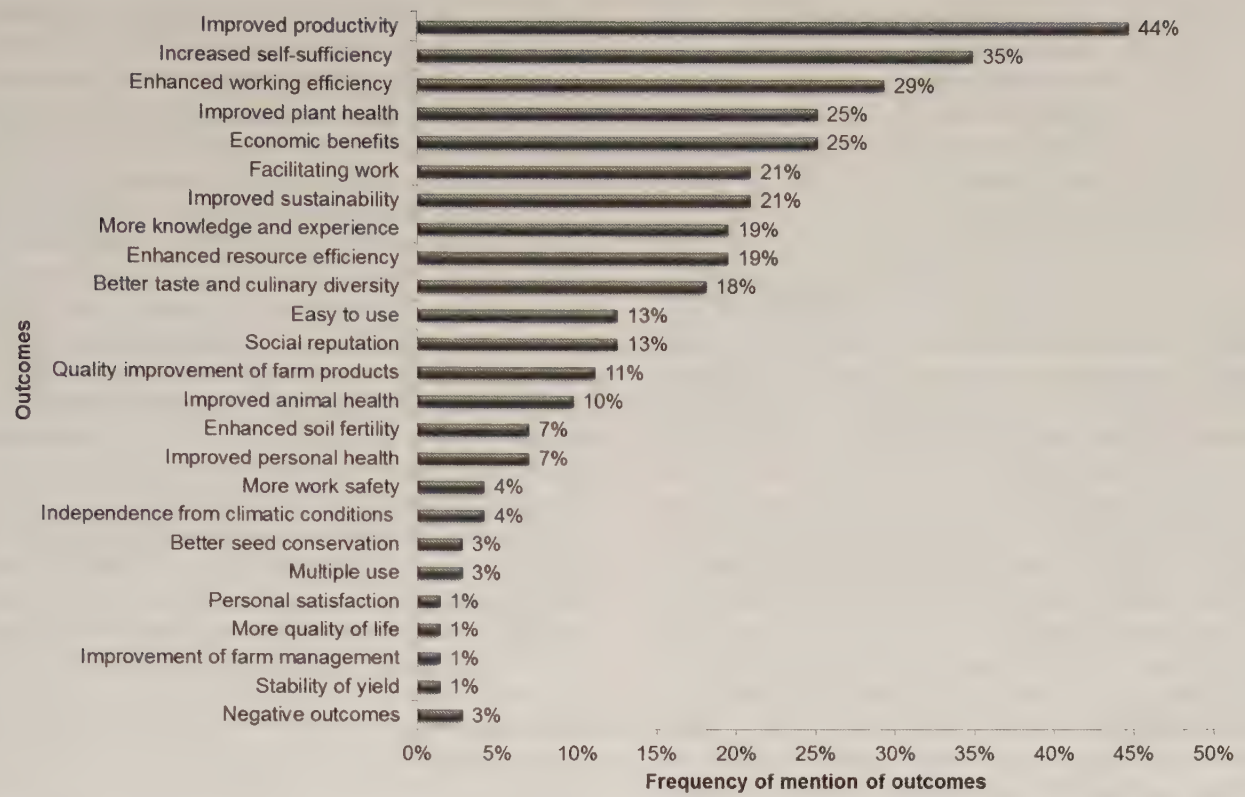
Improved productivity 44%
Increased self-sufficiency 35%
Enhanced working efficiency 29%
Improved plant health 25%
Economic benefits 25%
Facilitating work 21%
Improved sustainability 21%
More knowledge and experience 19%
Enhanced resource efficiency 19%
Better taste and culinary diversity 18%
Easy to use 13%
Social reputation 13%
Quality improvement of farm products 11%
Improved animal health 10%
Enhanced soil fertility 7%
Improved personal health 7%
More work safety 4%
Independence from climatic conditions 4%
Better seed conservation 3%
Multiple use 3%
Personal satisfaction 1%
More quality of life 1%
Improvement of farm management 1%
Stability of yield 1%
Negative outcomes 3%
Outcomes
0% 5% 10% 15% 20% 25% 30% 35% 40% 45% 50%
Frequency of mention of outcomes

Figure 5. Outcomes of farmers' experiments ($n = 72$; 100% = the total of all answers given by the respondents; multiple answers possible).

important contributions to family livelihood and welfare. All respondents relied on manual work as a crucial element of farming activities. Thus, enhancing working efficiency by reducing the workload was a major benefit of farmers' experiments. Respondents also mentioned improved plant health as a positive outcome of an experiment. Economic benefits included cost savings and income increase. Work facilitation was realized by making the labor more comfortable. Some respondents mentioned that the outcomes protected the environment and contributed to increased sustainability. Some respondents saw experimenting as a way to gather their own experiences and to learn about the topic. They figured out better ways of farming and thereby enhanced their local knowledge.

Respondents benefitted from experiments by improving the efficiency of resource applications and thereby economized production. Respondents acknowledged being independent from external food supply and appreciated diversifying their food choices. Experiments occasionally resulted in culinary benefits, which included better taste of farm products, easier preparation or higher food variety. Easy applicability of the outcome was another advantage mentioned.

A welcome side effect of an experiment's outcome was social reputation among the farmers' colleagues, extension agents or scientists. Respondents were proud of good working outcomes and enjoyed acknowledgement from others.

Interviewees reported higher quality of farm products because of their experiment. They observed improved animal health after experimenting with natural remedies and enhanced soil fertility after applying organic matter or worm compost. Respondents also mentioned health aspects as benefits. Experiments' outcomes decreased negative effects of agricultural production and thereby improved personal health. Higher work safety was also a benefit of experimenting.

Some experiments contributed to achieve independence from climatic conditions. Improved seed conservation, multiple uses of the outcomes for other purposes, personal satisfaction, better life quality, improved farm management and stability of the yield were less important benefits of the outcomes.

A few respondents mentioned experiments with negative outcomes, but they still reported to have benefitted in the form of increased knowledge about the experiments' topics. Even if farmers benefitted from their experiments, they also reported disadvantages. One important disadvantage was the resource input necessary to conduct an experiment with uncertain outcomes. Respondents dedicated working time to experimenting, which was deducted from regular farm work or spare time.

Dissemination of experiences

Respondents were usually proud of the outcomes and communicated them to others. Furthermore, outcomes

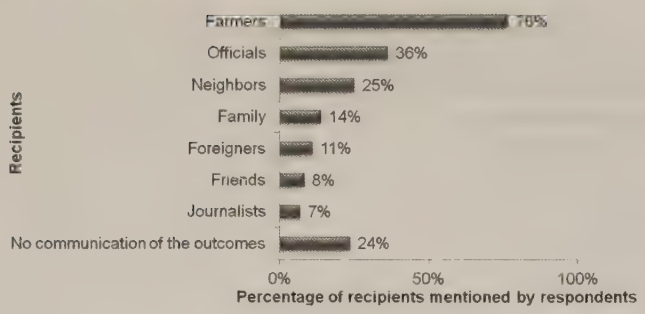

Figure 6. Dissemination of farmers' experiments in Cuba: people to whom respondents communicated the outcomes ($n=72$; 100% = the total of all answers given by the respondents; multiple answers possible).

that improved agricultural production awakened other farmers' interests. Local dissemination mainly took place within the farmers' peer network. Personal communication with other farmers was the most frequent channel for dissemination (Fig. 6).

Often, first recipients were other farmers within the family, close friends working in agriculture or neighboring farmers. After receiving positive feedback, farmers disseminated the outcomes on a larger scale. Most respondents addressed farmers' colleagues and other like-minded persons who lived in the same area and were supposed to benefit from the experiment. Agricultural officials, including advisors and scientists, also received information about the experiments' outcome. Interviewees also mentioned their outcomes when talking to neighbors and family members not working in the field of agriculture. Some respondents received visits from foreigners and explained the outcomes to them. Furthermore, a few respondents talked about the experiment with friends who did not work in agriculture. Some farmers explained their experiment to journalists.

Accepting farm visits and showing the outcomes to others reinforced the validity of the experiment. Visitors were mostly individual farmers or organized groups of farmers, extension agents, agricultural officials and representatives from farmers' associations. Some respondents presented their experiments in workshops organized by farmers' associations, research associations or by farmers themselves. Outstanding experiments or innovations appeared in magazines, journals or books written by scientists or journalists, or by farmers themselves.

Various Cuban institutions promoted farmers' participation at scientific and semi-scientific conferences to upgrade farmers' experiments. Farmers who developed remarkable innovations or inventions even participated at international conferences outside Cuba.

Some farmers wrote a text about their experiment on their own or with the help of extension agents or scientists to fulfill the requirements for participating at a conference or at Cuba's innovation award forum. Also, the monthly cooperative meeting represented a platform for knowledge exchange and dissemination of outcomes. Particularly active experimenters gave interviews for newspapers, radio or TV.

Farmers usually avoided talking about preliminary or negative outcomes to evade defamation or derision. Respondents preferred to go public only when they could provide evidence of the outcomes' validity and applicability. Experiments that had already been conducted by a majority of the local population were hardly communicated and respondents considered active promotion as redundant. Some interviewees considered their experiments as insignificant and refrained from dissemination. Farmers who applied for a patent and waited for a decision were more reserved when talking about the outcomes because they felt the need to protect their intellectual property.

Most experiments bear upon the local context, either upon farm level or upon community level. Occasionally, experiments were disseminated on a larger scale. Especially, participation at the innovation award forum, at workshops or conferences facilitated widespread dissemination and upgraded dissemination rates.

Discussion

Cuba's agriculture has undergone a series of structural changes during the course of its recent history[8,12]. Experimenting has been the farmers' approach to improve farming situations and livelihood conditions. The government's efforts to boost agricultural production have included the dissemination of technological innovations[57]. Experiments are farmers' means to adapt these innovations to site-specific conditions[31]. The broad diversity of topics and methods of farmers' experiments in Cuba results in a broad repertoire of potential adaptation strategies. Through experimenting farmers learn how to deal with multiple challenges of farming and increase the possible responses to changes that affect agricultural production.

The potential of farmers to experiment and their innovative capacity are widely accepted within the scientific community[24–31,33–36,40–43,45,58–66]. Most farmers are regularly and actively engaged in a wide range of different experiments[45]. Also in Cuba, farmers' experiments are an integral part of agriculture. Almost all farmers have engaged in activities with an experimental character on a diversity of topics and methods, and using a wide range of resources.

Increasing farm diversity is crucial to improve sustainability of agricultural systems[19]. Diversified production systems provide more opportunities to experiment and increase the farmers' capacity to experiment with different topics and methods. The amount of different stimuli *per se* provides multiple opportunities to learn how to deal with change.

Farmers' experiments are embedded in the local context, integrating locally available resources[34,45]. Resource

availability in Cuba has been affected by economic constraints that have resulted in resource shortages[67]. The farmers' way to deal with these constraints has been the search for alternative uses and reuses of discarded material. Farmers' experiments in Cuba were characterized by the use of locally available and often recycled resources. Cuban farmers showed creativity in recombining the available resources to improve their situation.

To initiate an experiment, farmers were most often driven by their own idea. However, respondents also mentioned a diversity of external ideas and factors as sources (other farmers, family members, agricultural officials, media, agricultural events, acquaintances and consumers). The farmers' own idea was also mentioned by most of the farmers in studies in East Africa[29], Austria[25] and Cuba[52]. Sumberg and Okali[29] found that farmers in Zimbabwe were experimenting based on external ideas, while farmers in Ghana claimed that experiments were based on their own ideas. Other authors referred to extension workers, research institutions and other farmers as sources of ideas for experimenting[40,68].

Most Cuban farmers started their experiments on a small scale to minimize risk. Small-scale experiments allowed the farmers to keep the experiment manageable. Small-scale experimentation was promoted by MACAC[13]. Other authors also mentioned small-scale experiments[29,30,44,68,69]. By conducting small-scale experiments, farmers gather experiences without the risk of threatening their sources of livelihood.

Direct observation was the most effective way for farmers to evaluate an experiment. Even farmers who applied scientific methods did not renounce careful observation. Some farmers used random sampling or repetitions during the experimental process. These procedures were mostly applied due to the academic background of the respondent and often adapted to their own requirements. Thus, expecting standardized methods would misconstrue the very nature of farmers' experiments. They are hardly comparable to standardized experimentation applied in academic research. Flexibility and adaptability of methods are key elements of farmers' experiments. Farmers have developed their own valid procedures to conduct and evaluate their experiments, and these are particularly suited to deal with the complexity of diverse farming activities and reflect the local conditions[70]. However, the institutional influence on farmers' experiments in Cuba, with MACAC and PIAL leading the way, shaped somehow the experimental process of farmers participating in their activities.

The experiments' outcomes usually improved the prevailing situation. The most important benefits were increased production and self-sufficiency followed by working efficiency, improved plant health, economic benefits, improved ease of work and sustainability, more knowledge and resource efficiency. Increased self-sufficiency and enhanced resource efficiency, especially, are linked to the resource scarcity triggered by the crisis. Even negative outcomes had their positive aspects. Learning from mistakes was an important step in adaptation processes. Farmers identified wrong approaches and learned how to improve, based on their experiences. At the same time, their accumulated experiences coalesced to a repertoire of local knowledge and practice. In our achievement-oriented society, mistakes have negative connotation, but they are crucial for learning, improvement and development.

Farmers gain and accumulate experience through their experiments. They integrate new experiences into the already existing knowledge pool and thereby amplify their local knowledge. Thus, farmers' experiments are means of learning on a self-paced basis according to their own perception of necessity. Farmers determine the intensity and velocity of this learning process[71]. Demonstrating and discussing experiments facilitate communication among farmers. When talking about their experiments, farmers make their knowledge and experiences explicit and thus exchangeable[26]. Farmers' experiments in Cuba were embedded in the local agricultural communication network. Personal interaction facilitated the transmission and exchange of knowledge. In addition, knowledge exchange platforms, such as workshops or innovation fairs, organized by members of MACAC or the PIAL project, facilitated dissemination of experiments' outcomes. Participation in these platforms potentially may trigger other experiments.

Dissemination of experiences from farmers' experiments in Cuba mainly took place within the farmers' peer network. Other farmers were the most important recipients of experiences. Cuban farmers also communicated their results to extension workers or scientists. Farmers' knowledge and their communication networks are key elements to enhance their adaptive capacity[71]. Informal and formal collaboration of farmers constitute encounters for knowledge exchange and represent an important base for adaptation strategies[72].

Farmers' experiments can be apparently insignificant activities, such as putting a seed into the ground. Even common agricultural practices can express experimental characteristics. The farmer's experience with the experiment's topic and the setting determine its experimental character. The experimental character might appear only if the experiment fails. In the case that everything works out fine, the farmer might not even be aware of the experimental character. Farmers might also experiment with common agricultural practices, which are widely known within the respective farming population. However, site-specific conditions usually differ from setting to setting. Therefore farmers' experiments are unique for the specific setting.

Conclusion

Farming conditions have changed constantly during the course of time[58]. Thus, the adaptive capacity of farmers is

crucial to cope with such changing conditions[72,73]. Experimenting allows farmers to increase their adaptive capacity[25]. However, farmers' experiments are unique for a specific setting, and transmission into another setting requires again adaptation to the new conditions. What needs to be transmitted is not so much the topic of an experiment or its outcome, but the spirit of being an experimenter and the methods for experimentation.

Farmers deal with experimental processes in a systemic way. By experimenting, they learn how to approach farm-specific problems and they increase their ability to assess various options for further activities. By doing so, they adapt and improve their farming system and contribute to agricultural development. Thus, farmers' experiments might be able to buffer disturbance of socio-ecological systems and represent crucial elements in preparing agriculture for prospective changes. Therefore, the empowerment of rural people as key actors for achieving long-term sustainability of agriculture and food systems must have priority in policy agendas.

In order to develop the full potential of farmers' experiments and innovations, decision makers have to recognize and support grassroots experimental activities. The Cuban experience of mitigating a food crisis and resource scarcity is an example of how farmers' experiments and innovations have been taken up as an important strategy to cope with severely changing conditions. Such strategies should be observed alertly, as similar situations might also affect other countries in the near future.

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Use of conservation practices by women farmers in the Northeastern United States

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Abstract

Women are the fastest growing segment of farm operators in the United States, comprising approximately 14% of principal operators and 30% of all operators of the nation's 2.2 million farms. Although several studies have examined the adoption of conservation practices by farmers, no study of which we are aware has focused on the use of conservation practices among women farmers in the US. Therefore, in 2008, we conducted a survey of women farmers in the Northeast US to better understand their use of conservation practices, and how their use is affected by demographic and farm characteristics, and membership in agricultural organizations and networks. We examined the practices related to the type of agricultural organizations, including commodity producer organizations, general farm organizations, women's groups associated with general farm or commodity organizations, farm women's organizations, and sustainable/organic agriculture organizations. Over 85% of the 815 respondents belonged to at least one organization. The most common organizations reported were sustainable/organic agriculture organizations (53.5%) and general farm organizations (50.8%). About one-third of respondents belonged to commodity-based organizations. The states with organized women farmers' networks—Pennsylvania, Maine and Vermont—represented more than half of them. Members of women's and sustainable or organic agriculture organizations tended to be younger, have less farming experience, and to have received more formal agricultural education than did members of commodity-based, general farm and women's agricultural groups within general farm organizations. Our results indicate that organizational membership and participation provide critical networks that support and reinforce the use of conservation practices. Some practices were positively associated with one type of organization while negatively associated with others. For example, compost production/application, crop rotation, manure incorporation, and organic crop and livestock production are more likely among members of sustainable/organic agriculture organizations, but less likely among members of general farm organizations. The converse is true for integrated pest management (IPM) on crop farms. Specific conservation practices had unique sets of variables linked to their use, with farm products being the most frequent predictors. This research serves as a baseline to understand the array of conservation practices used by women farmers in the Northeast US, and some factors associated with their use. The results suggest the need for consideration of the applicability of existing adoption models for women farmers. As women tend to have diversified operations with multiple markets, educational and regulatory programs that attempt to reach women farmers may need to consider the specific types of farms they operate to best match practices to their situations and goals.

Key words: women farmers, conservation practices and structures, environmental sustainability, agricultural organizations, women's agricultural networks

Increasingly, consumers and policy makers are demanding that agriculture perform multiple functions in addition to food and fiber production, from natural resource conservation and environmental remediation (e.g., carbon sequestration and mitigation of greenhouse gases) to rural economic development,

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conservation of open space and viewscapes, and recreational opportunities[1–4]. This multifunctional expectation for agriculture creates challenges for farmers, who are now expected to balance environmental quality, productivity, profitability and social responsibility[5].

Public recognition of the impact of agriculture on the environment has resulted in the creation of numerous programs managed by federal, state and local agencies in the US to conserve natural resources on agricultural lands. These programs, such as the Conservation Reserve Program (CRP) and Conservation Reserve Enhancement Programs (CREP), Conservation Security Program (CSP) and Environmental Quality Incentives Program (EQIP), promote and support land management practices and structures that reduce soil erosion, protect ground and surface water, increase wildlife habitat, and reduce damage caused by floods and other natural disasters. Participation in these programs requires that land managers implement those practices [best management practices (BMPs)] determined by agencies such as the Natural Resources Conservation Service (http://www.nrcs.usda.gov/) to reduce the environmental impact of agriculture and improve the condition of natural resources. Rates of adoption of these conservation practices and structures vary greatly due to differences in farm production systems, agroecological characteristics of the farm, farm business structure and farmer characteristics. Although there has been significant research examining the adoption of conservation practices[6], no study of which we are aware has focused on the use of conservation practices among women farmers in the US[7].

Women Farmers in the US

Women are the fastest growing segment of farm operator in the US[7]. In 1987, when the US Census of Agriculture first began identifying the gender of farm operators, women comprised 7% of all farmers. In 2002, the Census of Agriculture began counting farm operators in two capacities: as the principal operator and as one of multiple operators. Of the 3.3 million US farm and ranch operators on 2.2 million farms and ranches counted in the 2007 Census of Agriculture, women comprise 14% of the primary farm operators and 30% of all farm operators. These numbers of women principal operators of farms and ranches represent an increase of almost 30% between the 2002 and 2007 censuses.

Women-operated farms in the US differ from those operated primarily by men in several important ways[8]. Compared to all farms in the US, women-owned farms are small, diversified, and are more likely to be financially at-risk. Nearly 70% of women farm on less than 140 acres, approximately 80% report annual sales under $25,000, and they are more likely than male-operated farms to raise specialty crops or operate farms classified as 'other livestock farms,' which includes horse farms, or 'all other crops,' which includes hay farms[7]. By contrast, farms on which the primary operators are men are more likely to produce major commodities such grain, oilseeds and beef cattle.

Research over the past few decades has documented the sometimes hidden yet substantial roles women play on farms, including production, business management and decision-making, in addition to supportive and reproductive roles[8–14]. For example, Findeis et al.[15] found that 53% of farm women in their survey reported that they were major operators of their farms. Tasks in which women regularly participated include traditional (e.g., bookkeeping and running errands) as well as those related to farm production (e.g., taking care of animals, harvesting and fieldwork without machines). Women participated in important farm resource allocation decisions, including buying or selling land, buying major farm equipment, producing something new and trying a new production practice.

Concurrent with shifts in farm demographics has been the development of organizations that specifically target women farmers with education and assistance[16,17]. Traditional organizations that provide agricultural education, such as Cooperative Extension, have offered very limited production-focused education geared toward women farmers and their educational needs[10,12,17–20]. General US farm organizations, such as the Farm Bureau and the Grange, and commodity-based organizations historically have had women's affiliated groups, such as the Cowbelles, Porkettes and Wheathearts, that emphasize women's supportive or promotional role on farms[21]. More recently, organizations and networks have formed to specifically meet the needs of women farmers in the US, such as the Vermont, Maine and Pennsylvania Women's Agricultural Networks (WAgN; http://www.uvm.edu/~wagn/; http://www.umaine.edu/umext/wagn/; http://wagn.cas.psu.edu) and the Women, Food and Agriculture Network (WFAN; http://www.wfan.org/Women,_Food_and_Agriculture_Network_Home.html) in Iowa. These newer organizations typically utilize networks with a major goal of developing horizontal, peer-to-peer relationships for sharing experience-based information, social support and legitimacy as farmers[19,22–24]. These organizations offer educational opportunities that emphasize hands-on, interactive workshops, in which knowledge related to agricultural production, business management, and environmental and social sustainability is exchanged[17,23]. Women's agricultural networks and similar organizations developed in large part in response to the historical lack of information from conventional agricultural institutions, such as land-grant universities, about the use of alternative agricultural technologies, such as organic production and grazing-based livestock production[25–31].

Conservation Practices

To better understand women farmers' use of conservation practices, multiple sets of individual, farm, household and economic characteristics, as well as the types and strength of social relationships of farmers should be considered[6,32]. There are few consistent predictors of adoption of conservation practices by US farmers[6,27,33–37], but that may not be necessarily true for women farmers.

Some characteristics that farmers use to evaluate technologies and practices include initial and long-term cost, labor requirements, the impact on production, profitability, and other farm enterprises, complexity of the practice, and the extent to which the technology or practice will confer an economic advantage or disadvantage[38,39]. Smit and Smithers[40] identified perceptions of the effectiveness of a practice for site-specific, biophysical farm conditions as an important barrier to adoption. Perceptions of the institutions that teach about or support the technology, and perceptions of the distribution of benefits and costs, can influence farmers' evaluation of the technology or practice[32].

Relatedly, characteristics of the farm itself, e.g., scale, profitability, markets, type of products, diversity of products, topography, labor availability and ownership structure, can influence the applicability of a particular practice or technology[6]. Size of farm and scale of production have generally been found to be positively associated with the adoption of conservation practices[6,41,42]. Farmers with more available resources, particularly capital, can invest in conservation practices and are more likely to realize tax benefits[43,44]. Landowners, compared to those who lease land, are more likely to adopt conservation practices because they have greater management flexibility and control[41,45]. Other farm characteristics that may influence adoption include the commodity produced, existing production practices, landscape characteristics and marketing strategies[32]. The diversity of enterprises within the farming operation may be positively related to adoption of conservation practices, as diverse-enterprise farms may be in a better position to experiment, and more types of practices are applicable. However, a farm that is over-diversified can be negatively associated with adoption of conservation practices because the farmer may not be able to sort through the multiple options that would apply to the different enterprises of the farm operation[46].

Individual actions regarding the natural environment take place within a context of social relationships and structural conditions[47–49]. Family and household characteristics, including number of people in the household, age of household members, off-farm work, location of decision-making authority and plans for the future of the farm, may influence adoption. For example, younger farmers are more likely to adopt conservation practices, presumably because they have longer planning horizons for the farm[6,50]. A farmer's individual resources, such as education and experience on the farm, also contribute to likelihood of adoption. The availability of labor—either hired or non-paid family labor—is positively associated with the adoption of conservation practices[41].

Farmers' individual beliefs and attitudes influence adoption of conservation practices, although inconsistencies in measurement make these relationships difficult to interpret[6]. In general, concern over environmental consequences of agricultural production influences the likelihood of adoption[40]. Farmers with an environmental orientation may weigh the costs and benefits of a particular practice or technology using different criteria, including environmental risks, risks to future generations' use of the land and resources, and risks to downstream users of the resources. Some farmers are willing to forego profit in favor of using farm practices that reflect environmental stewardship goals[34].

Farmers take into consideration the degree of congruence between the use of the technology and the goals that the farmer has for the farm. A related factor is the 'fit' between the goals of the technology and farmers' identities, such as producers, environmental stewards, entrepreneurs and innovators[51]. Further, a farmer's perceptions of how others in the community will judge the farm (and the farmer) using the new technology or practice affect a farmer's willingness to adopt a practice[35,49].

Organizations and Networks

In empirical studies, membership in formal organizations has shown limited but potentially positive impacts on adoption of conservation practices[32]. Formal organizations can be crucial information resources for learning about conservation practices[37]. Smit and Smithers[40] argue that membership in farmers' organizations indicates a progressive attitude or a willingness to seek new knowledge, which has been positively associated with adoption of conservation practices.

New types of organizations and networks have emerged to support farmers who either have personal characteristics (gender and ethnic background) or a farming type (organic, pasture-based, etc.) that have created barriers to accessing traditional educational resources. These new sources of information and support can significantly influence these farmers' practices, their levels of success and their identities as legitimate farmers[52,53]. Classical adoption/diffusion theory emphasizes the importance of social networks in two key stages of the process, awareness and evaluation[39,54]. Networks consisting of 'weak ties' (e.g., acquaintances), bring new information and ideas, such as BMPs, to an individual farmer[37]. Weak tie networks can raise awareness of conservation issues and support the identification of conservation problems on individual farms[40]. Networks consisting of 'strong ties' (e.g., family, close friends and advisors) play a significant

role as farmers evaluate new information and technologies as to the fit to their farm and situation[6,32,55–58]. Discussions of the practice or technology with those most familiar with the individual farmer's circumstances can assist farmers as they think through its applicability and potential impacts on the farm and its management[38]. These discussions can build on the trust and knowledge that is embedded in the relationships between network participants[27,59]. Higher levels of trust within these relationships enhance the likelihood that farmers will discuss the new practices within their core network, which increases the propensity of adopting the practice[55].

In comparison with other innovations studied in classical adoption/diffusion research, networks become particularly crucial for adoption of conservation practices. In studies of non-conservation practices, the innovation is often a private good, with identifiable short- and long-term benefits for producers. In contrast, conservation practices result in more public than private goods, with short-term costs for the producer and uncertain long-term benefits[44,60]. Additionally, the environmental benefits of conservation practice adoption to an individual farmer depend partly on the decisions of other producers when they share a common-pool resource such as a watershed, exacerbating uncertainty[60]. Localized networks of producers can help ameliorate the collective action problem by creating a forum for sharing information about use of conservation practices and the establishment of new conservation-focused norms and expectations for action[48,53,61].

An important outcome of farmer participation in organizations and networks can be changes in self-identity, which can enhance conservation efforts. One approach of network-based conservation programs is to integrate new conceptualizations of farmers' roles as environmental stewards into their existing identities as business owners, entrepreneurs and innovators[53,62,63]. These new identities require thinking about activities in relationship to the environment in different ways, or redefining what are considered 'good' farming practices[51,63]. Networks provide forums for exploring potential new approaches without threatening existing identities. Networks also provide key locations for sharing of knowledge among experts and practitioners that can lead to more effective management practices[27,59,62,64].

The growth in numbers of women farmers, their role in farm management and decision-making, and their potential role in transferring conservation-related information, support the critical need to understand the impact of organizations on women farmers' use of conservation practices. Yet, we know relatively little about the conservation practices used by women farmers in the US. To what extent are women farmers practicing conservation techniques that enhance environmental quality? What are the characteristics of women farmers and their farms associated with using conservation practices? The ability to identify the characteristics of conservation practice adopters and non-adopters will affect the ability of educators and service providers to reach this audience with appropriate information and resources. Therefore, we conducted a survey to determine the use of specific conservation practices among women farmers in the Northeastern United States. We report these practices in relation to farm and farmer characteristics, including organizational and network membership. Based on the literature reviewed, we hypothesized that demographic characteristics, farm scale and participation in agricultural organizations will affect the use of conservation practices by women farmers.

Methods

To characterize women farmers in the Northeast US and examine our hypotheses about use of conservation practices, we conducted a survey of women farmers in the Northeast United States. For the purposes of this study, the Northeast is comprised of nine states: Pennsylvania, New York, Maine, New Hampshire, Connecticut, Massachusetts, Vermont, New Jersey and Rhode Island. We define women farmers as women who live on a farm and participate in farm labor and/or decision-making. As there was no publicly available list of women farmers in the region for the survey, a sampling frame was built by drawing from multiple sources, including membership directories, advertising materials and brochures, and web sites of farming organizations. Organizational sources represented multiple agricultural sectors, including traditional commodity producers (e.g., state-based labeling programs), sustainable or organic producers (e.g., Northeast Organic Farming Association, Pennsylvania Association for Sustainable Agriculture), and women's agricultural organizations (e.g., Vermont WAgN and Pennsylvania WAgN). Farms included in the sampling frame produced products prevalent in the region, including dairy, grains and oilseeds, horticulture, livestock and livestock products, fruit, greenhouse/nursery, specialty and value-added products (e.g., maple syrup, seeds, wine, etc.), or had other farm-based enterprises, e.g., agritourism such as bed and breakfasts, corn mazes, tours, etc. or educational programs.

Surveys were sent to a sample of 2000 farms drawn randomly from this sampling frame during the winter of 2007–2008. A modified Dillman method was used to administer the mail survey, including a five-contact mailing procedure (pre-notification, survey, reminder postcard, reminder with a survey and a final reminder letter) and a $1 incentive payment[65]. Labels and letters were addressed to the female name in the sample. If a female name was not available, the label was addressed to the 'Female Household Member' at the farm address. A total of 815 completed surveys were received, for a response rate of 40.7%.

Table 1. Use of structures and practices applicable for crops ($n = 549$ respondents with row or horticultural crops).

	Number of respondents reporting as applicable	Percentage reporting presence/use in past 3 years[1]
Structure		
Permanent vegetation on slopes	426	81.0
Conservation buffers, permanent field borders, hedgerows, or windbreaks	478	79.9
Riparian buffers or filter strips (forest vegetative)	371	66.3
Grassed waterways or swales	369	61.0
Improved stream crossing	297	46.5
Fenced waterways	339	30.1
Contour buffer strips	357	30.0
Practice		
Crop rotation	499	90.4
Soil testing	530	84.2
Cover crops	496	82.3
Compost production or application	511	80.6
Mulching	483	79.1
Organic production	505	77.4
Conservation residue or tillage management	436	66.1
Manure incorporation after application	430	65.3
Hay or perennial forage planting	446	62.1
IPM	453	57.4
Contour or strip cropping	380	31.8

[1] Calculated as the percentage of those who reported having row or horticultural crops and who reported the structure or practice as applicable to their farms.

Key Variables

Use of conservation practices

To construct questions related to use of conservation practices, we used structural and management criteria developed by the USDA Natural Resources Conservation Service (http://www.nrcs.usda.gov/programs/eqip/). Decision or evaluative tools based on these conservation structures and management practices have been developed by the agency to determine eligibility of farmers for enrollment in various government support programs that promote agricultural production and environmental quality as compatible goals. We included a subset of these management practices and physical structures in the survey, and listed them separately for crop (Table 1) and for livestock production (Table 2). Respondents were asked to indicate if they had used the practice in the past 3 years (yes/no) or if the structure was currently present on their farm (yes/no), or if the practice or structure was not applicable to their farm. Tables 1 and 2 list each practice/structure and the percentage of respondents reporting its use, based on applicability for the type of farm.

Farm and farmer characteristics

We collected information on age, level of education, total household income in 2007, race/ethnicity, off-farm work, and the contribution of off-farm work to household income (Table 3). Survey questions related to farm characteristics include type of livestock and crops produced and scale of production (i.e., acres, number of livestock and gross farm income) (Table 4).

To determine the scale of the operation across different types of livestock, we calculated animal equivalent units (AEU) developed in local land use planning ordinances that fit the livestock types used in the survey and did not require differentiation by age of the animal. The animal equivalents used included: dairy cow, 1.33; beef cow, 1.0; horse, 2.0; hog, 0.4; sheep, 0.1; goat, 0.16; turkey, 0.0182; and chicken, 0.01. Aggregated results will appear over 100.00.

To assess the role of environmental considerations in farm planning, respondents indicated the importance (not, somewhat, moderately, or very important) of statements related to how they assess the success of their farms. Statements reflected goals related to environmental quality, profitability, building community relationships and quality of life (Table 5). Factor analysis produced three summative rating scales that reflect different measures of success in farming: (1) environmental sustainability (improving soil quality, improving environmental quality, and providing healthy food), (2) community relationships (being respected in my community, maintaining good relationships with other farmers, maintaining a high quality of life, and enjoying what I am doing), and (3) profitability (increasing profitability,

Table 2. Use of structures and practices applicable for livestock ($n = 503$ respondents with livestock).

	Number of respondents reporting as applicable	Percentage reporting presence/use in past 3 years[1]
Structure		
Permanent vegetation on slopes	442	77.6
Grassed waterways or swales	382	54.7
Riparian buffers or filter strips (forest or vegetative)	389	53.5
Composting facility	445	45.4
Improved animal trails or walkways	393	42.5
Fenced waterways	374	41.2
Barnyard run-off control	394	38.8
Contour buffer strips	365	24.1
Protected solid or liquid waste storage facility	378	17.7
Stream side watering systems	352	15.6
Practice		
Management intensive, rotational, or prescribed grazing	439	71.3
Pasture or hay planting	460	63.9
Following a nutrient management plan	429	56.9
Organic livestock production	448	51.1
Manure transfer	395	50.4
IPM	403	31.5

[1] Calculated as the percentage of those who report having livestock and who report the structure or practice as applicable to their farms.

satisfying customers, and increasing production yields). As summarized in Table 5, reliability of these scales is satisfactory; the Cronbach's alpha values are 0.62 for the three-item scale related to environmental quality, 0.60 for the four-item scale related community relationships, and 0.62 for the three-item scale related to profitability.

Participation in organizations

Participation in farm-related organizations was measured with multiple questions. First, respondents were asked to indicate formal membership (registered or dues-paying), either currently or within the past 3 years, in five distinct types of organizations. The options included commodity producer organizations (e.g., American Dairy Association and Fruit and Vegetable Growers Association), general farm organizations (e.g., Farm Bureau and Grange), women's groups associated with general farm or commodity organizations (e.g., Farm Bureau Women), farm women's organizations (e.g., Vermont Women's Agriculture Network and Women Involved in Farm Economics), and sustainable/organic agriculture organizations (e.g., Pennsylvania Association for Sustainable Agriculture, Maine Organic Farmers and Growers Association, and Northeast Organic Farming Association). These organizations differ significantly in their approach to information sharing (e.g., expert-to-learner versus peer-to-peer learning), topics they address, and willingness to explore alternative approaches to agriculture[66]. These differences raise the possibility that the structure and orientation of organizations may affect the type and scope of information about conservation practices that is conveyed to farmers.

Higher levels of participation may increase exposure to ideas shared within the organization or network and the level of trust and degree of embeddedness within the organizations[60]. Respondents were asked to indicate the frequency with which they participate in various activities of these organizations, such as visiting websites, reading publications, communicating with staff and other members, attending educational events and serving in leadership positions. The response categories included not applicable, never, sometimes, frequently and always. A scale was then created that summed respondents' answers to these activities to represent level of organizational participation. Reliability of the scale is satisfactory, with a Cronbach's alpha of 0.83[67].

The third measure of participation accounts for differences in the type of organization by measuring reasons for joining the organization. Survey respondents were asked to indicate the importance (not, somewhat, moderately or very important) of 14 potential reasons for joining farm organizations. Factor analysis was conducted on these items, and resulted in the development of three summative rating scales that reflect distinct types of reasons for joining: (1) to learn about production, (2) to develop business and personal networks, and (3) to advocate for farmers, women farmers or the food system. Reliability of these scales is satisfactory[67]; Cronbach's alpha values are 0.88 for the three-item scale related to

Table 3. Selected demographic characteristics of survey respondents.

Respondent characteristics	Percentage of respondents
Age	
Under 25 years	0.8
25–34 years	9.7
35–44 years	17.0
45–54 years	31.9
55–64 years	28.2
65–74 years	10.0
75 years and over	2.4
Formal education related to agriculture	18.7
Level of education	
Less than high school grade	2.1
High school grade	11.9
Vocational or technical school	6.6
Some college	22.5
4-year degree	27.4
Post-graduate education	29.5
Off-farm paid job	51.1
Percentage of household income from wage/salary job	
None	26.1
1–25%	13.9
26–50%	10.3
51–75%	10.6
76–100%	39.2
Household income from all sources in 2006	
Less than $10,000	4.9
$10,000–$29,999	17.1
$30,000–$49,999	21.5
$50,000–$74,999	24.1
$75,000–$99,999	13.4
$100,000–$249,999	15.5
$250,000 or more	3.7
State	
Pennsylvania	19.6
Maine	18.9
Vermont	17.5
New York	16.0
Massachusetts	12.9
Connecticut	4.4
New Jersey	4.2
New Hampshire	3.8
Rhode Island	2.7

learning about production, 0.87 for the five-item scale related to developing networks and 0.89 for the four-item scale related to advocacy.

Statistical analyses

Survey data were analyzed using the statistical software package SPSS version 16.0[68]. Statistical analyses presented include descriptive statistics (i.e., percentages, means, medians, standard deviations and ranges). For the purposes of the multivariate analyses of farm characteristics, farms were classified into a series of bimodal types reflecting key farm characteristics and scale indicators, such as farms growing agronomic crops (corn, soybeans or grains; $n=260$), farms growing horticultural crops (small fruits, tree fruits, vegetables, tobacco or nursery; $n=487$), and those producing any livestock ($n=503$). Scale is denoted by both acreage and number of livestock using quartiles as cut points. Large farms are those with more than 61 AEU or more than 177.5 acres; small farms are those with less than 4.5 AEU or less than 20 acres. As the structures and management practices are binary variables, bivariate and multivariate analyses include measures of association (Goodman and Kruskal's tau), non-parametric correlations (Spearman's rho) and logistic regression.

To address hypotheses related to the use of conservation practices by women farmers, we used logistic regression models for each management practice in crop production and livestock production systems. The model chi-square statistics indicate the degree of improvement of the specified model over a baseline model; larger chi-square values indicate greater improvement[69].

Results

Demographic profile of the women farmers

The average age of respondents to our survey was 51.2 years. The distribution across age categories reflects a mix of ages, with about one-quarter (27.5%) under 44 years of age, about one-third (31.9%) between 45 and 54 years of age, about one-quarter (28.2%) between 55 and 64 years of age, and 12.4% over the age of 65 (Table 3). Nearly all (89.0%) respondents were Caucasian. A small percentage (2.6%) indicated they are members of the Anabaptist community. One-quarter (28.7%) of respondents indicated that they grew up on a farm or ranch. Respondents were relatively highly educated, with more than half (56.9%) holding a college or post-graduate degree. Fewer than one-quarter (18.7%) received formal education in agriculture (Table 3).

Household income varied within the sample (Table 3). About 5% indicated that total household income from all sources was below $10,000. Over one-third (38.6%) reported household income between $10,000 and $50,000. A similar percentage (37.5%) reported income between $50,000 and $100,000. About one-fifth (19.2%) of the sample reported income above $100,000. About one-half (51.1%) of the respondents worked off the farm in a salary or wage job. Approximately half of the respondents (49.8%) indicated that the source of half or more of their household income was an off-farm job. About one-quarter of respondents (26.1%) reported that they receive no household income from an off-farm job.

Table 4. Selected farm characteristics of survey respondents ($n = 815$).

Farm characteristics	Percentage of respondents
Producing row or horticultural crops	73.9
Vegetables	52.6
Small fruits and brambles	30.7
Pasture	27.6
Horticulture plants/nursery/flowers	25.0
Alfalfa/hay	24.4
Tree fruits/nuts	18.7
Corn/soybeans	16.6
Producing livestock	66.4
Chickens (layers)	37.9
Horses	26.7
Beef cattle	21.6
Hogs, pigs	21.2
Other poultry	19.4
Sheep, lambs	19.3
Dairy cattle	19.1
Goats, kids	18.7
Chickens (broilers)	18.5
Gross farm sales	
Less than $10,000	36.4
$10,000–$49,999	26.9
$50,000–$99,999	12.0
$100,000–$249,999	13.3
$250,000 and over	11.3
Total acres (rented and owned)	
1–9 acres	12.1
10–29 acres	19.3
30–49 acres	10.5
50–99 acres	15.4
100–199 acres	19.7
200–499 acres	16.7
500 acres or more	6.4
Membership in organizations	
Sustainable/organic agriculture groups (e.g., Pennsylvania Association for Sustainable Agriculture, Maine Organic Farmers and Growers Association)	53.5
General farm organization (e.g., Farm Bureau or Grange)	50.8
Commodity producer associations (e.g., American Dairy Association or Fruit and Vegetable Growers Association)	36.8
Farm women's organization (e.g., Vermont Women's Agriculture Network or Women Involved in Farm Economics)	20.6
Women's groups associated with general farm or commodity organizations (e.g., Farm Bureau Women)	10.5

Farm characteristics

The respondents' farms were generally small. About one-third (36.4%) reported gross farm sales of less than $10,000, with an additional quarter (26.9%) between $10,000 and $50,000 (Table 4). Nearly three-quarters of the sample (73.9%) produced row or horticultural crops, while two-thirds (66.4%) produced livestock (Table 4). The primary crops grown included vegetables (52.6%), small fruits and brambles (30.7%), pasture (27.6%), horticulture plants, nursery or flowers (25.0%), and alfalfa/hay (24.4%). The primary livestock on the farms in the sample are laying hens (36.7%), horses (26.7%), beef cattle (21.6%) and hogs (21.2%) (Table 4).

A majority of the sample (71.7%) sold their products through direct retail outlets or directly to consumers. Nearly three-quarters (74.6%) of the sample used at least one strategy to add value to their farm products, such as

Table 5. Descriptive statistics for interval level variables.

	Mean	Standard deviation	Range	Cronbach's alpha
Participation level scale (7 items)	14.5	4.2	2.0–28.0	0.83
Scales of reasons for joining organizations				
To learn about production (3 items)	9.4	2.5	3.0–12.0	0.88
To network (5 items)	13.4	4.1	3.0–20.0	0.87
To advocate (4 items)	11.8	3.5	1.0–16.0	0.89
Scales of farm goals				
Environmental quality (3 items)	13.7	1.8	4.0–15.0	0.62
Building relationships (4 items)	18.2	2.1	8.0–20.0	0.60
Increasing profitability (3 items)	10.6	2.3	3.0–15.0	0.54
Age	51.2	12.0	15–85	NA

organic and specialty production, on-farm processing or agritourism.

The scales of farm goals were reported as the high mean values for three scales measuring importance of building relationships (18.2 with a maximum value of 20), environmental quality (13.7 with a maximum value of 15), and increasing profitability (10.6 with a maximum value of 15) (Table 5).

Organizational participation

Most respondents (86.5%) reported membership in at least one organization; more than half (55.8%) belonged to two or more organizations (Tables 4 and 5). The most common organizations among respondents were sustainable/organic agriculture organizations (53.5%) and general farm organizations (50.8%). About one-third of respondents (36.8%) belonged to commodity-based organizations. Respondents were less likely to be a member of women's farm-related organizations, with 20.6% reporting membership in women's agriculture organizations. The states with organized women farmers' networks—Pennsylvania, Maine and Vermont—represented more than half of those (56.0%) (Table 3). Because of the small percentage of respondents (10.5%) who were members of women's groups within general farm organizations, this category was deleted from further analyses. The scale of organizational participation was reported as the high mean value (14.5 with a maximum of 28) (Table 5).

Organizational participation and conservation practices

Level of participation in organizations was positively but weakly associated with use of conservation practices. Higher levels of participation were related to an increase in the odds of using compost production/application (9%), conservation residue and tillage management (8%), crop rotation (11%), organic production (8%), integrated pest management (IPM) for livestock (7%) and organic livestock production (8%).

Reasons for joining an organization tended to be weakly associated with use of conservation practices, both positively and negatively. Women farmers who reported joining organizations to improve productivity and profitability were more likely to use soil testing (18%) and IPM for both crops (13%) and livestock (17%), and less likely to use organic livestock production methods (14%). Those who reported networking as a main benefit from organizational membership also reported a lower likelihood of using IPM for livestock (12%) and rotational or other management intensive grazing systems (10%), and greater likelihood of using compost production/application (11%) and manure incorporation (14%). Women farmers who reported advocacy for farms, women farmers and local foods as a major reason for organizational membership were less likely to use soil testing (14%) and manure incorporation (14%), and more likely to use organic livestock production (14%), rotational or other management intensive grazing systems (20%) and nutrient management planning (15%).

Use of conservation structures and management practices

Of the structures and practices listed by respondents for crop production systems for whom the structure or practice is applicable, all but three structures (improved stream crossings, fenced waterways and contour buffer strips) and one management practice (contour or strip cropping) were used by more than half of respondents within the past 3 years (Tables 1 and 2). Large percentages of respondents reported using conservation practices, such as conservation buffers (79.9%), riparian buffers (66.3%), crop rotation (90.4%), cover crops (82.3%) and conservation tillage (66.1%). Nearly three-quarters (77.4%) report using organic crop production practices.

Significant percentages of respondents with livestock reported use of conservation practices (Tables 1 and 2). For example, respondents reported using structures that are intended to protect water quality, such as improved animal trails (42.5%), fenced waterways (41.2%) and barnyard run-off control methods (38.8%). Similarly,

Table 6. Logistic regression models predicting likelihood of use of conservation practices related to crops.[1,2]

	Compost production or application ($n=393$)	Conservation residue and tillage management ($n=349$)	Contour or strip cropping ($n=303$)	Cover crops ($n=384$)	Crop rotation ($n=389$)	Hay/ perennial forage planting ($n=354$)
Producing agronomic crops	0.89	1.42	**4.25*****	**2.89****	**2.23+**	**4.42*****
Producing horticultural crops	**2.91***	1.45	0.74	**2.21+**	**4.45****	0.69
Producing livestock	**2.55***	0.76	**0.27****	**0.43***	1.33	**2.88****
Farm with >61 AEU[3]	0.67	0.84	0.84	**0.33***	1.04	1.37
Farm with <4.5 AEU	1.99	0.90	1.93	**6.52****	1.10	0.89
Farm with >177.5 acres	0.93	0.80	0.87	0.78	1.31	1.31
Farm with <20 acres	**5.65****	1.41	1.31	0.67	2.09	**0.39***
Gross farm income	0.88	**1.25+**	1.06	**1.59****	1.26	1.22
Age	1.01	1.00	1.02	0.99	1.01	1.01
Education	1.05	1.02	0.93	0.98	0.98	**0.79***
Formal agriculture education	1.02	1.36	1.64	1.19	0.98	**2.54***
Work off-farm	1.04	0.68	1.07	0.85	1.08	**1.70+**
Goals—environmental quality	**1.29***	1.17	1.12	**1.26***	**1.31***	1.04
Goals—building relationships	**0.87+**	0.95	0.93	1.13	1.10	0.99
Goals—increasing profitability	1.03	0.99	**1.13+**	1.02	1.00	1.01
Commodity producer organizations	1.35	0.83	1.11	0.58	1.26	0.88
General farm organizations	**0.57+**	0.87	0.88	0.69	**0.29****	0.69
Women's agricultural organizations	0.71	1.30	0.69	0.82	0.69	1.11
Sustainable/organic agricultural organizations	**2.37***	1.15	1.38	**2.41***	**2.56***	1.06
Level of organization participation	**1.09+**	**1.08***	1.00	1.06	**1.11+**	1.01
Join to learn about production	0.98	0.98	1.04	1.08	1.13	0.91
Join to network	**1.11+**	1.06	1.05	0.99	1.03	1.05
Join to advocate	1.00	0.98	0.96	0.94	0.87	1.03
Model chi-square	100.48***	33.77+	43.67**	87.14***	54.63***	124.41***
Log Likelihood	302.08	420.40	336.27	294.94	211.64	342.15
Nagelkerke *R*-square	0.35	0.13	0.19	0.32	0.26	0.41

	IPM ($n=357$)	Manure incorporation after application ($n=327$)	Mulching ($n=377$)	Organic production ($n=390$)	Soil testing ($n=409$)
Producing agronomic crops	0.73	1.32	0.78	1.13	**2.77****
Producing horticultural crops	**4.29*****	**2.32***	**9.90*****	1.57	0.88
Producing livestock	0.57	**3.37****	1.43	1.54	**0.28****
Farm with >61 AEU	**0.26****	0.96	0.82	1.18	1.28
Farm with <4.5 AEU	1.58	2.16	2.04	**2.90+**	1.06
Farm with >177.5 acres	0.90	0.97	0.56	0.94	1.00
Farm with <20 acres	0.96	1.19	**3.05***	**9.41*****	0.90
Gross farm income	**1.84*****	1.00	1.00	**0.77+**	**1.34+**
Age	1.02	1.01	1.02	1.01	1.00
Education	0.88	0.88	1.00	1.08	**1.31***
Formal agriculture education	1.52	**2.10***	0.92	0.95	0.60
Work off-farm	1.25	1.45	0.92	0.85	**0.49***
Goals—environmental quality	1.07	1.13	**1.26***	**1.54*****	1.19
Goals—building relationships	0.94	1.04	0.89	0.99	1.02
Goals—increasing profitability	1.03	1.05	0.91	0.96	1.07
Commodity producer organizations	**1.65+**	1.38	1.38	0.77	1.36

Table 6. (*Cont.*)

	IPM ($n=357$)	Manure incorporation after application ($n=327$)	Mulching ($n=377$)	Organic production ($n=390$)	Soil testing ($n=409$)
General farm organizations	1.36	**0.57+**	1.08	**0.43***	1.03
Women's agricultural organizations	1.23	**2.20***	2.26	0.89	1.15
Sustainable/organic agricultural organizations	**0.54+**	**2.09***	1.16	**3.61*****	**2.19***
Level of organization participation	0.95	0.98	1.07	**1.08+**	1.06
Join to learn about production	**1.13+**	1.02	1.07	1.12	**1.18***
Join to network	0.93	**1.14***	0.99	0.92	1.00
Join to advocate	1.03	**0.88***	1.00	1.01	**0.86***
Model chi-square	107.70***	74.17***	111.32***	145.79***	70.48***
Log likelihood	378.06	348.70	275.75	280.33	284.36
Nagelkerke R-square	0.35	0.28	0.39	0.47	0.264

[1] Coefficients reported are estimated odds ratios [Exp(β)]; values above 1.00 indicate positive association with use of practice/structure.
[2] Significant values are indicated by $+P<0.10$, $*P<0.05$, $**P<0.01$, $***P<0.001$.
[3] Animal equivalence units (AEU): dairy cow = 1.33, beef cow = 1.0, horse = 2.0, hog = 0.4, sheep = 0.1, goat = 0.16, turkey = 0.0182, and chicken = 0.01.

respondents indicated use of practices related to nutrient management, with more than half (56.9%) following a nutrient management plan and half (50.4%) using manure transfer practices. Nearly three-quarters (71.3%) reported using rotational or other managed grazing, and about half (51.1%) reported using organic livestock production methods.

Most models for the use of crop conservation practices were statistically significant, with the exception of the model for conservation tillage ($P<0.10$) (Table 6). Pseudo-R^2 measures (Nagelkerke R^2) provide general guidance as to model fit, although strictly speaking, cannot be interpreted as the percentage of variance explained. For crop-related measures, the overall model fit for each practice varied, from a low of 0.13 for conservation tillage to a high of 0.47 for organic production. All chi-square statistics for the models of the livestock conservation practices are significant. For livestock-related measures, pseudo-R^2 measures (Nagelkerke R^2) indicate the overall model fit for each practice varied, from a low of 0.16 for IPM and manure transfer to a high of 0.32 for organic livestock production (Table 7). In general, the specified models are relatively weak predictors of adoption of conservation practices related to livestock production.

Exponentiated logistic regression coefficient [Exp(B)] values indicate the change in odds of the dependent variable associated with a change in value of the independent variable (Tables 6 and 7)[69]. Exact interpretation depends on the level of measurement of the independent variables. For example, producing horticultural crops (binary) has an exponentiated coefficient of 2.91 for compost production/application. Women farmers who produce horticultural crops have a 191% increase in the odds [(2.91–1)*100] of producing/applying compost on their farms. Similarly, producing livestock (155%), having small acreage (465%) and being a member of a sustainable/organic agricultural organization (137%) increases the odds of compost production/application.

Continuous variables, such as the scales related to goals and organizational participation, can be interpreted such that a unit change in the independent variable is associated with a change in odds of adopting the practice. For example, a one-point increase in the scale of goals related to environmental quality results in an increase in the odds of using compost production/application by 29%. Similarly, a one-point increase in level of organizational participation relates to an increase in the odds of using compost production/application by 9%; a one-point increase in the scale of joining agricultural organizations to network relates to an increase in the odds of using compost production/application by 11%. Variables that decrease the odds of using compost production/application include farm goals related to building community relationships (13%) and membership in general farm organizations (43%). This constellation of variables indicates that use of compost production/application is most likely to occur on smaller, diversified livestock/vegetable farms, in which the farmer is interested in improving environmental quality and participates in sustainable/organic agricultural organizations, but not general farm organizations.

Table 7. Logistic regression models predicting likelihood of use of conservation practices related to livestock.[1,2]

	IPM ($n=306$)	Management intensive, rotational, or prescribed grazing ($n=329$)	Manure transfer ($n=295$)	Following a nutrient management plan ($n=325$)	Organic livestock production ($n=332$)	Pasture or hay planting ($n=343$)
Producing agronomic crops	1.08	1.08	1.05	1.03	0.94	**3.94*****
Producing horticultural crops	1.64	0.75	**1.94***	**1.67+**	0.99	0.65
Farm with >61 AEU	1.05	1.33	**2.44***	**4.32*****	1.62	1.92
Farm with <4.5 AEU	0.82	**0.37****	0.59	0.74	1.05	0.65
Farm with >177.5 acres	0.65	1.44	0.89	0.84	1.19	0.81
Farm with <20 acres	1.49	1.50	1.28	1.33	0.76	0.99
Gross farm income	**1.24+**	0.94	0.90	1.11	0.89	1.14
Age	1.02	**0.96****	1.01	1.02	1.01	1.00
Education	1.01	1.07	0.99	1.02	**0.75****	0.94
Formal agriculture education	1.43	1.07	0.95	1.18	0.88	**1.90+**
Work off-farm	0.98	1.21	0.93	1.18	1.39	1.54
Goals—environmental quality	1.01	1.10	0.99	1.05	1.17	1.03
Goals—building relationships	1.01	0.96	0.99	0.97	1.07	0.91
Goals—increasing profitability	0.97	0.95	**1.14***	1.07	1.00	1.03
Commodity producer organizations	**1.87***	1.20	**1.85***	**1.76***	**0.49***	0.97
General farm organizations	1.05	0.76	1.17	1.04	0.72	1.05
Women's agricultural organizations	**2.00***	1.10	1.28	0.88	0.90	0.67
Sustainable/organic agricultural organizations	0.65	**2.01***	1.62	0.78	**5.10***	1.22
Level of organic participation	**1.07+**	1.05	0.98	0.99	**1.08***	0.98
Join to learn about production	**1.17***	1.09	1.11	1.01	**0.86***	1.02
Join to network	**0.88***	**0.90+**	0.99	0.99	0.95	0.97
Join to advocate	1.05	**1.20****	1.07	**1.15***	**1.14***	1.05
Model chi-square	36.19*	63.63***	36.84*	48.48**	90.16***	66.623***
Log likelihood	351.96	335.392	372.118	394.03	370.043	377.82
Nagelkerke *R*-square	0.16	0.25	0.16	0.19	0.32	0.24

[1] Coefficients reported are estimated odds ratios [Exp(β)]; values above 1.00 indicate positive association with use of practice/structure.
[2] Significant values are indicated by $+P<0.10$, $*P<0.05$, $**P<0.01$ and $***P<0.001$.
[3] Animal equivalence units (AEU): dairy cow = 1.33, beef cow = 1.0, horse = 2.0, hog = 0.4, sheep = 0.1, goat = 0.16, turkey = 0.0182, and chicken = 0.01.

Farms producing agronomic crops (i.e., corn, soybeans and grains) are more likely to use contour/strip cropping (increased odds by 325%), cover crops (189%), crop rotation (123%), hay/perennial forage planting (342%), soil testing (177%) and pasture/hay planting (294%). Farms growing horticultural crops (i.e., small fruits, tree fruits, vegetables, tobacco or nursery) have higher odds of using compost production/application (191%), cover crops (121%), crop rotation (345%), IPM for crops (329%), manure incorporation (132%), mulching (890%), manure transfer (94%) and follow a nutrient management plan (67%). Farms with any livestock have higher odds of adopting compost production/application (155%), hay/perennial forage planting (188%) and manure incorporation (237%); these farms have lower odds of contour/strip cropping (73%), cover crops (57%) and soil testing (72%).

Discussion

Demographic profile of the women farmers

Overall, our findings provide detailed information about women farmers in the Northeast US. Respondents to our survey differed from US averages for several demographic

characteristics, e.g., they were younger and derived a lower percentage of their household income from an off-farm source. The average age of respondents to our survey was 51.2 years, younger than the average age of all US farmers (54.9 years), all US principal operators (57.1 years), and average age of all female principal operators (54 years)[7]. We hypothesized that farmer age would be negatively associated with adoption of conservation practices. We found that age was not generally associated with the use of conservation practices by women farmers in our survey. Age of respondent was only associated with a small decrease (4%) in the odds of using rotational or other management intensive grazing in our sample. This is in contrast to Soule et al.[50] and Prokopy et al.[6], who found that age can have a negative effect on the adoption of conservation practices due to relatively shorter planning horizons.

About one-half (51.1%) of the respondents worked off the farm in a salary or wage job. According to the 2007 Census of Agriculture[7], 80.5% of women farm operators earn less than 25% of total household income from the farm, and approximately 87% derive more than half of total farm income from an off-farm source. In our sample, a much lower percentage, approximately half of the respondents (49.8%), indicated that the source of half or more of their household income is an off-farm job.

The majority of the respondents received an education beyond high school, and we hypothesized that level of education would be positively related to use of conservation practices. However, education level had a varied association with use of conservation practices. For example, respondents with more education had a lower likelihood of planting hay/perennial forages (21%) and organic livestock production (25%), but higher likelihood of soil testing (31%). This result is in contrast to Caswell et al.[41] and Prokopy et al.[6], who found that years of education and farming experience were positively related to use of conservation practices. Those authors hypothesized that more educated and experienced farmers are exposed to more ideas and have more experience in making decisions. A minority percentage of respondents in our survey received a formal agricultural education, but having a formal agricultural education increased the odds of planting hay/perennial forages (154%), manure incorporation (110%) and planting pasture or hay (90%). These practices are also associated with livestock production (Table 6), and may reflect practices common to dairy and other livestock farms in the Northeast US.

We hypothesized that farmer orientation relative to the environment would be positively related to adoption of conservation practices. In our sample, farm goals (improving environmental quality, building relationships and increasing profitability) showed some relationships with several conservation practices. Higher values on the scale related to improving environmental quality as a measure of farm success were related to increased likelihood of using compost production/application (29%), cover crops (26%), crop rotation (31%), mulching (26%) and organic production (54%). This provides limited support for research that has found an association between environmental orientation and use of conservation practices[6,34].

Farm characteristics

Women farmers in our sample reflect national trends in the US related to scale of farm (small), type of farm (diversified, predominantly horticulture and livestock) and use of diversified marketing strategies (a high proportion of direct marketing and value-added strategies). In our survey, the respondents' farms were generally small. The mean total number of acres operated (owned and rented) was 150 acres. However, 41.9% of respondents operated less than 50 acres. Over 60% reported gross farm sales of less than $50,000. These numbers are consistent with the 2007 US Census of Agriculture[7], which reports that nearly 80% of women-operated farms had annual sales under $25,000. A key difference between our sample and national data relates to the balance of farm and non-farm household income. Our sample included more women farmers for whom the farm provides significant household income.

We hypothesized that farm resources, such as type, income and scale of production, would be positively related to the use of conservation practices. Farm type, in particular, conditioned which conservation practices 'fit' the farm. Farm product (agronomic crop, horticultural crop and livestock) was the most consistent and strongest predictor of use of the various types of conservation practices analyzed.

Farm scale is a routine predictor; however, we speculate the causal mechanism may not be additional resources available to farmers of larger scale farms. As women tend to operate small, diversified farms, scale in terms of acreage or number of livestock may not be an accurate indicator of access to capital or other resources. Instead, scale of production might be an indicator, along with main farm product, of a type of farm. Scale in terms of gross farm income may be a better indicator of resources, and it was associated with some conservation practices (IPM, conservation tillage, cover crops and soil testing) most often associated with larger, conventional agronomic crop farms. These findings also suggest a need for development of a typology of farm 'types' that include the types of diversified farms owned and operated by women farmers. Educational and technical assistance related to conservation practices could be prioritized and targeted to match these particular types of farms.

The relationships between farm scale and conservation practices varied. Larger livestock farms (the top quarter of our sample in number of AEU) had a lower likelihood of using cover crops (67%) and IPM methods for crops (74%); they had a higher likelihood of using manure transfer (144%) and following a nutrient management

plan (332%). The latter two practices are linked to regulatory requirements only applicable to large-scale livestock farms.

Farms in the bottom quarter in number of AEU had a greater likelihood of using cover crops (552%) and organic crop production (190%), but a lower likelihood of rotational or other managed grazing (63%). In rotational or other management intensive grazing systems, livestock are regularly and systematically moved to fresh paddocks to maximize the quality and quantity of forage growth[70]. Even though managed grazing has demonstrated economic and environmental benefits, continuous grazing is the most common grazing system in the US[71]. Farmers who have low numbers of animals may choose to use continuous grazing because, compared with intensively managed grazing systems, capital investment is lower because of lower fencing and watering facilities requirements. Time commitment can be lower and management decisions can be simpler in continuous grazing systems because intensively managed grazing systems require careful monitoring of livestock and the pasture resource. The inverse association between cover crop use, which is used mainly in annual cropping systems[72], and management intensive grazing may reflect a focus of resources and management effort on crop production with lower investment in animal production.

Large scale in terms of acreage (> 177.5 acres) was not associated with use of conservation practices. Small acreage farms (< 20 acres) had a higher likelihood of using compost production/application (465%), mulching (205%) and organic crop production (841%). Although size of farm has generally been found to be positively associated with the use of conservation practices[6,41,42], our findings suggest that the relationship between size is likely mediated by production practices, and type and mix of products on the farm. Of the 20,437 organic farms in the US, over 45% produce on less than 9 acres, and approximately 70% produce on less than 49 acres[7]. As certified organic producers in the US are prohibited from using synthetic fertility or weed control inputs, they must rely on substances such as composts, and green and animal manures to manage soil fertility. Cultural practices, such as tillage and mulching with cover crop or crop residues can be used to suppress weeds. In 2007, 51.3 and 65% of US organic farms reported using organic mulch or compost, or animal or green manures, respectively[7]. Our results agree with the use of these conservation practices on small acreage organic farms.

Our final measure of scale, gross farm income, has several significant coefficients. An increase in category of gross farm income is associated with an increased likelihood of using conservation residue and tillage management (25%), cover crops (59%), IPM for crops (84%) and for livestock (24%), and soil testing (34%); it is associated with a decreased likelihood of organic crop production methods (23%). These results suggest that larger scale is linked to a suite of practices used largely on traditional dairy/agronomic crop farms. These findings suggest some support for the general finding in the literature that increased capital offers resources with which farmers can make investments associated with conservation practices[6,43].

The size of farms may also relate to their profitability. Data from respondents of our survey revealed a strong association of organic production and farms of less than 20 acres (Table 6). In the US, approximately 65% of all farms are small (median size 69 acres), and of those, 73% of fall into a sales class of less than $10,000, and about 30% fall into a sales class of $10,000–49,000[73]. Profitability measures are strongly associated with farm size. The average operating profit margin and average rates of return on assets and equity are negative for small farms, but positive for large-scale farms. Households operating small farms typically receive substantial off-farm income. In 2008, more that half (50.7%) of organic farms earned less than 49% of their net household income from farm sales, and most of those (45% of all organic farms) earned less than 25% of their net household income from farm sales[7].

Consistent with census results on women farmers[7], farms in our sample are diverse and emphasize non-commodity farm products. However, our sample differs significantly from the national averages for organic farming and direct marketing of farm products. In 2007, organic farms comprised only 9.3% of all US farms, with women comprising 22% of principal operators of organic farms. In contrast, nearly 50% of the women farmers in our sample reported using organic production methods. Also in marked contrast to US averages, a majority of the respondents to our survey (71.7%) sold their products through direct retail outlets or directly to consumers. One of the differences between conventional and organic food marketing is the use of direct markets—an estimated 1.6% of US fresh produce sales are through direct sales, while approximately 7% of US organic food sales occur through marketing channels other than retail stores[7]. Nearly three-quarters (74.6%) of our sample used at least one strategy to add value to their farm products, such as organic and specialty production, on-farm processing or agritourism.

The generally small size of women's farms in our sample, and their location in the Northeast US, may contribute to the observed differences from the national data for direct marketing and other value-added strategies, such as organic production. In 2007, there were 136,817 farms in the US, or about 6% of the total number, that sold agricultural products directly. Nearly all US farms that engaged in direct sales were small farms, which accounted for 93.3% of all farms engaged in direct sales and generated 56.7% of the total value of agricultural products sold directly to consumers. The majority of farms in our sample can be considered small, with only 3.7% reporting household income from all sources of $250,000 or more. California has the most direct sales of agricultural products, accounting for 13.4% of total direct

sales followed by New York and Pennsylvania, with 6.4 and 6.3% of total direct sales, respectively. These results raise questions for further research as to why these women are more likely to engage in organic farming and direct marketing or other value-added practices.

One could speculate that organic production and direct marketing may be means for women farmers to increase their profitability. On average, organic farms in the US have an average operating profit nearly double that for all farms, $45,697 for organic versus $25,448 for all farms[7]. However, we observed a negative relationship between gross farm income and organic crop production. The negative relationship between gross income and organic production may have differed if we had measured net income, because production expenses are higher on organic farms than on conventional farms. On average, US certified and exempted (sales < $5,000/year) organic farms incur production expenses of $171,978 per farm; higher than the $109,359 average for all farms nationwide[7]. Even though average production expenses are higher on organic farms than on non-organic farms, organic farms had an estimated average net income that was $20,249 per farm per year higher than the all-farm figure[7].

Organizational participation and use of conservation structures and management practices

The majority of women farmers in our survey belong to one or more types of agricultural organizations or networks. These organizations provide a range of services for women farmers, including information about production and conservation as well as the opportunity to advocate for farmers or specific production systems. Relatively large percentages of women farmers reported using recommended conservation practices. For example, conservation or reduced tillage, buffers, nutrient management, and weed and pest management techniques, such as cover crops and IPM, were practiced by more than half of farmers in our sample (with the exception of IPM for livestock production).

We hypothesized that participation in agricultural organizations will be related to a greater likelihood of adoption of conservation practices. The results related to organizational membership and participation indicate that agricultural organizations provide critical networks that support and reinforce the use of conservation practices. Membership in any organization was positively associated with adoption of several practices. Exceptions include the negative relationships between membership in general farm organizations and organic production and other practices linked to smaller scale farms (compost production, crop rotation and manure incorporation). Membership in sustainable or organic agriculture organizations was negatively related to use of IPM, which raises questions about the interpretation of conservation practices as listed on a survey such as ours. For example, IPM is an approach to managing pests by a broad range of practices, including biological, cultural, physical and chemical tactics. Its use often relies on sampling crops to determine the abundance of pests and beneficial organisms for use in decision-making about therapeutic treatment with pesticides, but also includes the pre-emptive use of genetically modified crops and pesticide-protected seed. In organic crop production systems, which were over-represented in our sample, the choice of therapeutic materials for controlling pests are extremely limited and genetically modified crops and their associated technology package (e.g., insecticide-coated seed) are not allowed. Reporting on the use of IPM may depend on the interpretation by the respondent of the specific practices involved.

In contrast, membership in a commodity producer organization increased the odds of using IPM (crops and livestock), manure transfer and nutrient management planning; while membership in a commodity producer organization decreased the odds of organic livestock production. Membership in a general farm organization decreased the odds of using compost production/application, crop rotation, manure incorporation and organic crop production. Membership in women's agriculture organizations increased the odds of adopting manure incorporation and IPM in livestock. Membership in sustainable/organic agricultural organizations increased the odds of compost production/application, cover crops, crop rotation, manure incorporation, organic crop production, soil testing, rotational or other management intensive grazing, and organic livestock production; membership in this type of group decreases the odds of adopting IPM for crops.

Of interest are those practices in which membership in one type of organization is positively associated, and membership in another organization is negatively associated, with use of particular practices. For example, the odds of using compost production/application, crop rotation, manure incorporation, and organic crop and livestock production are all increased if the farmer is a member of a sustainable/organic agriculture organization, but decreased if the farmer was a member of a general farm organization. The converse is true for IPM for crops. The success of IPM in non-organic production systems is often due to the availability of efficacious and cost-effective synthetic chemical pesticides. Many IPM systems developed for non-organic crops are based on the pre-emptive use of pest control materials (e.g., genetically modified crops and insecticidal seed treatments) or assessment of pest populations and reaction to them with the use of 'therapeutic' materials (chemical or biological) in a timely, but reactive way. In comparison with non-organic production systems, the numbers of allowable pest control materials that can be used in a reactive way in organic production systems is extremely limited and may only be used after all other approaches have proved ineffective

(USDA National Organic Program, http://www.ams.usda.gov/AMSv1.0/nop). Often, information on the efficacy of a material allowable in organic systems for a specific pest is lacking. The cost of some allowable materials can be quite high. Therefore, even if an allowable, efficacious pest control material is available, its cost may exceed the benefit that might be gained from controlling the pest[74].

There is a likelihood that membership in these different organizations reflects larger differences in production practices, product type, farm structure and demographic characteristics. For example, members of sustainable/organic and women's farm organizations were significantly younger, had been farming for fewer years, were more likely to have formal agriculture-related education and operated fewer acres than members of other types of organizations.

Conclusions

The results indicate some support for relationships found in previous literature, but suggest the need for further consideration of the applicability of existing models for women farmers[75]. Demographic characteristics (age, education and off-farm work) found influential in previous work were not routinely associated across all areas of conservation practices in our study. We suggest the need to reconsider the causal mechanisms related to these demographics and further research their interaction with other key characteristics, such as gender, household composition and decision-making roles. The complexity of business and family arrangements on many farms, particularly farms where women play significant or primary roles, means that models which gather data on a single operator may not adequately capture the dynamics of conservation-related decisions[15,38].

This research serves as a baseline to describe conservation practices used by women farmers in the Northeast US, and some of the factors associated with their use. Based on our results, future research could investigate factors that would be likely to increase women farmers' use of conservation practices and structures on their farms, e.g., the extent to which they farm on lands likely to experience environmental degradation from agricultural practices, the extent to which they perceive environmental degradation to be a problem on their farm, their access to information about costs and benefits of conservation practices, their access to programs that support their adoption and their rate of application to those programs.

Information on women's use of conservation practices can also be used to inform policy and program development as well as techniques and strategies for reaching this growing audience with appropriate conservation information and support. Each practice had unique sets of variables linked to the likelihood of use, and farm products are the most frequent predictors of use. Consequently, the applicability of each practice is tied to the specific mix of products on each farm. As women tend to have diversified operations with multiple markets, educational and regulatory programs that attempt to reach women farmers may need to consider the specific types of farms they operate. Technicians and other personnel may need to develop in-depth knowledge of these farms to best match practices to their specific situations and goals[17,18,23,76]. Further, as only one-quarter of respondents grew up on a farm or ranch, and fewer than one-quarter received formal education in agriculture, educators and policymakers may need to determine, develop and offer support and educational programs that target the specific level of knowledge of this audience.

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Soil properties in organic olive orchards following different weed management in a rolling landscape of Andalusia, Spain

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Abstract

This study evaluated the most significant physical, chemical and biological soil properties from a group of organic olive farms located in a typical olive-growing area of Andalusia, Spain, after 5 or more years since the shift from conventional to organic farming, and compared soils with those in nearby undisturbed (U) natural areas. Two soil management systems implemented in these organic olive farms to control weeds, tillage (T), characterized by non-inverting-shallow tillage in spring, and mechanical mowing (M), were compared and evaluated against the U areas. Organic olive orchards showed similar productivity (average fruit yield of 3130 kg ha^{-1} yr^{-1}) as the conventional, rain-fed olive groves in the same area, with no significant differences due to soil management systems. Soil properties in the olive orchards (i.e. texture, pH, organic carbon (C), organic nitrogen (N), C:N ratio, cation exchange capacity (CEC) and exchangeable potassium) were in the suitable range for olive farming in both soil managements, although organic C and N, saturated hydraulic conductivity and available water-holding capacity (AWC) of the soil were lower than in the U areas. A principal component analysis (PCA) for soil properties in topsoil (0–10 cm depth) distinguished the T from M olive orchards and U areas, and determined organic C and N as the most significant soil properties to characterize them. Average values of soil organic carbon (SOC) stocks for the surface layer (0–10 cm depth) were 18.6, 59.3 and 67.8 Mg ha^{-1}, for T and M soil management systems and U areas, respectively. This indicates that the sustainability of organic olive orchards could be significantly improved by shifting to M soil management to decrease soil erosion and depletion of SOC.

Key words: olive groves, organic farming, soil management, soil properties, sustainability

Introduction

Andalusia, the southernmost region of Spain, is the main olive-growing area in the world, producing more than one-third of the world's olive oil[1,2]. Olive groves dominate the landscape of Andalusia on approximately 1.5 million-ha or 17% of the total surface area of the region. Despite a recent trend toward new intensive olive groves in valley areas, almost half of the olive farms are located on slopes steeper than 15% and 80% of the olive grove acreage is rain-fed[1,3]. Traditional olive orchard management is based on low tree densities (< 140 trees ha^{-1})[3], tree crown size is controlled by pruning, and weed control through repeated tillage and/or herbicide use, in order to sustain production in areas where rainfall is limited and highly variable from year to year. The combination of a Mediterranean-type climate with periodical torrential rainstorms, sloping areas and management practices that fail to provide ground cover year-round, is associated with severe problems of soil erosion in many olive-farming areas of Andalusia, accompanied by soil fertility depletion, biodiversity loss and environmental degradation[4,5].

In the past decade, a growing number of olive farmers in Andalusia have shifted from conventional to organic farming. In 2011, there were over 56,000 ha of organic olive groves[1], with 40% located in the province of Córdoba. This shift to organic olive production in Andalusia has accelerated the adoption of sustainable management practices aimed at soil conservation, in addition to the prohibition of synthetic fertilizers and pesticides. Milgroom *et al.*[6] reported that the shift to organic olive production in the province of Córdoba was accompanied by a reduction in tillage and an increase

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in grazing livestock or mechanical mowing to control weeds, which decreased the risk of soil erosion, based on a visual assessment of erosion[6,7]. However, little is known about the effects of shifting from conventional to organic farming on soil properties based on different soil management practices in olive orchards of Andalusia, where organic farming was officially regulated in 1991. Álvarez *et al.*[8] showed that organic olive orchards in a mountainous area in the north of Córdoba had soil properties (i.e., bulk density, macroaggregate stability, saturated hydraulic conductivity, phosphorus (P), potassium (K), cation exchange capacity (CEC), soil respiration and bacterial population) similar to those in natural adjacent areas, although generally lower in the tilled than in the grazed organic olive groves, but organic carbon (C) and nitrogen (N) tended to be higher in natural areas than in organic olive groves. However, these olive groves were in mountainous areas characterized by steep slopes and low productivity, where farmers have traditionally employed very low-intensity management systems[6,8].

In Andalusia, where olive tree cultivation is of great socio-economic importance, the most representative olive groves occupy about three-quarters of the total olive-grove area, and are located on hills and rolling plains with level to moderate slopes (below 20%)[3]. In these intensified, traditional rain-fed olive groves, farmers typically manage weeds throughout the year through repeated tillage and/or herbicide application with the primary goal of reducing weed competition for scarce water resources. In Campiña (natural region, in the southern part of Córdoba province, characterized by a rolling landscape), the shift to organic olive production has resulted in a decrease in tillage intensity without herbicides, and in an increase in mechanical mowing to control weeds[6]. The objective of this study was to evaluate soil properties in organic olive groves under different soil management systems in Campiña, more than 5 years after conversion from conventional to organic farming, comparing them with soil properties in nearby undisturbed areas with natural vegetation.

Materials and Methods

Study site and organic olive farm characteristics

The study area was located in Campiña, south Córdoba, (between 37.75° – 37.20°N and 4.67° – 4.17°W). The climate in the area is typically Mediterranean, with an average annual rainfall of around 560 mm, concentrated between November and April, an average mean annual temperature of 16°C, and an average annual reference evapotranspiration (ETo) of 1250 mm. Elevation in the study area ranges from 230 to 593 m.

Twenty rain-fed organic olive farms were selected in Campiña for the study. Organic olive farms were characterized based on the number of years since the farms were certified as organic. The main soil types on the farms were Calcaric Regosol and Calcic Cambisol[9]. Two soil management systems to control weeds were identified: tillage (T) and mechanical mowing (M). Five olive farms were selected for each soil management system in each soil type. Additional conditions for a farm to be selected included at least three decades of olive production and use of their current soil management system for at least the five preceding years. Information about organic olive farms was collected from the Andalusian Committee of Ecological Agriculture (CAAE; a control, certification and training organization) database. Six undisturbed (U) areas with natural vegetation typical of the Mediterranean maquis (i.e., sclerophyll and aromatic perennial shrubs) were selected to serve as benchmark soils for U areas. U areas are not frequent in the study area; so three U areas adjacent to the olive groves were selected in each of the two soil types.

Each farmer was interviewed for a complete description of their olive-farming practices and fruit yields over the past 3 years. Soil management prior to organic management was bare soil, controlling weeds by tillage and/or spraying with herbicides. The T system, defined as non-inverting-shallow T, consisted of three passes of a chisel-plough and/or cultivator (10–20 cm depth) in the spring, after rainfall events and weed growth; and usually one pass of a tine-harrow in the summer. Weed management with a mechanical mower (usually a reel mower) was performed one to three times a year during the spring, depending on weed growth. Therefore, the cover remained during the winter. Fertilization of olive orchards was similar regardless of the soil management system, providing generally 3–4 kg of organic fertilizer (14.3% N, 0.65% P and 4.41% K; N-plus, Nitrorganic S.L., Cabra, Spain) per tree per year. In general, olive pruning was completed every 2 years and the pruning residues were chopped and incorporated into the soil ($\sim 1.2\,Mg\,ha^{-1}$). Pruning consisted of thinning of branches using hand tools to improve lighting inside the tree, and the shortening of the upper branches.

Field measurements, soil sampling and analysis

Fieldwork was conducted in late spring 2006. On each farm, a sampling area, considered representative of the olive orchard, was selected. Within each sampling area, olive tree planting density was determined by measuring tree distances (between and inside rows). Olive tree crown volume was determined by measuring the crown major axes in five representative olive trees, and calculated assuming an ellipsoidal shape. Tree crown cover was calculated as the product of the mean horizontal crown area and olive tree density. A representative sampling area was also selected in each natural area.

Soil sampling and measurements were carried out outside the canopy of the tree. Slope was measured at five random points with a pocket inclinometer. Vegetative and stone ground covers were measured by the visual

Table 1. Soil physical, chemical and biological properties analyzed, and analytical methods used.

Parameters	Method
Laboratory analysis	
Particle size distribution (%)[1]	Hydrometer method[12]
WS aggregates ($g\,kg^{-1}$)[2]	Protocols of Barthès and Roose[13]
Organic C ($g\,kg^{-1}$)	Walkley–Black method[14]
Organic N ($g\,kg^{-1}$)	Kjeldahl method[15]
Extractable P ($mg\,kg^{-1}$)	Olsen method[16]
Exchangeable K ($mg\,kg^{-1}$)	Ammonium acetate method[17]
CEC ($cmol\,kg^{-1}$)	Ammonium replacement method[18]
pH (H_2O)	1:2.5 suspension in water
pH (KCl)	1:2.5 suspension in KCl
Soil microbial respiration ($mg\ CO_2\ kg^{-1}\,day^{-1}$)[3]	OxiTop control method[19]
Bacterial population ($cfu\,g^{-1}$)[4]	Plate dilution method
Soil microbial functional diversity (H')[5,6]	Biolog-GN2 MicroPlate system[20]
Calculated parameters	
K_{erod}[7] ($t\,h\,(MJ\,mm)^{-1}$)	Renard et al.[21]
AWC[8] ($m\,m^{-1}$)	Difference in SWC[9] at −33 and −1500 kPa
C:N ratio	Ratio organic C to organic N
SOC[10] ($kg\ organic\ C\ m^{-2}$)	Calculated from soil organic C content

[1] Coarse sand (2.0–0.1 mm) and fine sand (0.1–0.05 mm) were separated by wet sieving.
[2] Water-stable aggregates separated into WS-microaggregates (<0.02 mm), WS-mesoaggregates (0.02–0.2 mm) and WS-macroaggregates (>0.2 mm) on a basis free of coarse sand (>0.25 mm).
[3] 100 g of soil (dry weight) moistened to 50% of soil water-holding capacity and 50-ml beaker filled with a 1 M NaOH solution in an incubation cabinet (WTW, Weilheim, Germany) at darkness and 20°C for 1 day.
[4] Suspension of 5 g soil in 50 ml of 0.85% w/v NaCl solution, shaken for 60 min, centrifuged at 150*g* for 3 min, diluted from 10^{-1} to 10^{-4}, and inoculated in duplicate using 0.1 ml onto nutrient agar (Difco, Detroit, MI, USA) plates; viable bacterial colonies (colony-forming units, cfu) were counted after 4 days, incubation at 22–24°C.
[5] Calculated using the Shannon diversity index (H')[22].
[6] Biolog GN2 MicroPlate system (Biolog Inc., Hayward, CA), containing a water-blank well and 95 different C sources for identification of aerobic Gram-negative bacteria; each of 96 wells of microplates inoculated with 120 µl suspension of 2 ml from 1:10 dilution (5 g soil in 50 ml of 0.85% w/v NaCl solution) in 18 ml of 0.85% NaCl solution, and incubated at 25°C; colour development measured every 12 h up to 312 h by reading absorbance at 595 nm.
[7] Soil erodibility estimated from field measurements and soil analysis.
[8] Available water-holding capacity of the soil.
[9] Soil water content, estimated using particle size distribution, bulk density, stone volume, organic C and CEC measurements[23].
[10] Organic C stocks in any soil layer taking into account bulk density and stone volume.

method of Herweg[10] in ten random areas (0.5 m × 0.5 m each). Water infiltration rate was measured at five random points using single rings (21.5 cm diameter) inserted 5 cm into the ground, in tests lasting 1.8 h with constant water depth of 4 cm. Field-saturated hydraulic conductivity (K_s) was calculated from the data obtained in the water infiltration rate tests[11]. Soil bulk density was measured at eight random points using a cylindrical core sampler (5.0 cm diameter, 5.0 cm high) at two soil depths (0–10 and 10–20 cm).

Soil samples for laboratory analyses were collected at five random points in each sampling area, at two soil depths (0–10 and 10–20 cm) (Table 1). Soil structure was determined visually[24] in each of the two soil depths. Soil samples were air-dried, and passed through a 2-mm sieve before chemical and physical analyses. Samples for the determination of soil biological properties were collected at five random points (0–10 cm depth) in all sampling areas during the same day, July 12, 2006; soil was sieved through a 2-mm screen, and refrigerated at −20°C within 24 h of the sampling.

Energy consumption

Energy consumption in mechanical operations (non-inverting-shallow T or mechanical M) for weed control included energy consumption of machinery and implements (tractor and cultivator/chisel-plough or mechanical mower) and human labor. Basic data for calculating the energy consumption of machinery and implements were obtained from Guzmán and Alonso[25]. The diesel fuel energy (content plus industrial manufacture) was $43.33\,MJ\,l^{-1}$, and estimated average of diesel fuel consumption for tractor was $0.151\,kW\text{-}h^{-1}$. With regard to human labor, a value of $2.2\,MJ\,h^{-1}$ was used[25,26]. Thus, the total energy requirements were approximately $644\,MJ\,h^{-1}$ for both weed control strategies (tractor 4 × 4, 90 kW; and mechanical mower or cultivator of similar weight, 700 kg, and hours of useful life, 2500 h)[25], of which 91% ($585\,MJ\,h^{-1}$) was attributable to diesel fuel consumption. Although the total time required for each weeding operation was variable, depending on the specific tractor and farm implements

used and soil conditions (e.g., slope, stoniness), in organic olive farms in this study it reached 2 h ha^{-1} for the most unfavorable conditions (i.e., 1.29 GJ ha^{-1} of energy consumption).

Statistical analyses

Separate one-way analyses of variance (ANOVA) of soil properties were performed for each soil depth, with soil management system and soil type as factors. To satisfy ANOVA assumptions, field-saturated hydraulic conductivity and bacterial population data were log-transformed by $\log(x+1)$ and $\log(x)$, respectively, before analysis[27]. Statistical results (P values) relate to transformed data.

To investigate the effects of soil management system and soil type on soil properties at farm level, a standardized principal component analysis (PCA)[28], based on a correlation matrix, was performed for the topsoil layer (0–10 cm depth), using untransformed data. Soil type and management system effects on specific soil properties were assessed using standardized scores of the most significant principal components (PCs) for each individual olive orchard and U area.

Results

Olive orchard characteristics

The organic olive orchards evaluated averaged 3130 kg ha^{-1} yr^{-1} in olive fruit yield for 2003–05, with no significant differences due to soil management system (Table 2), although the relatively high farm-to-farm variability in yield suggests that in order to detect possible differences at the level of the values observed, a larger sample, if possible, should be included in future studies. The average yield was similar to the average value for rain-fed olive groves in the study area (3211 kg ha^{-1} yr^{-1} for 2003–05)[1]. Tree density was relatively low (average of 106 trees ha^{-1}), similar to that in the traditional rain-fed olive groves in the study area (112 trees ha^{-1})[3]; however, the trees have two or three trunks, forming relatively large canopies (average crown volume of 66 m^3 tree^{-1}), which covered 25% of the ground (Table 2). Exposed stones covered 11% of ground surface. The vegetative ground cover in late spring was 61% in the mowed orchards, as in U areas, compared with 9% in tilled orchards (Table 2).

Soil properties

There were no differences for any of the soil physical and chemical properties analyzed (Table 3) in the soil surface (0–10 cm depth) between the two soil types ($P>0.1$; Table 3). In the soil sub-surface (10–20 cm depth), similar results were obtained (Table 4). A comparison of values between surface and sub-surface values showed a decrease in available water-holding capacity (AWC) of the soil, organic C content and soil organic carbon (SOC) stocks, nutrient content (N, P and K) and C:N ratio, and an increase in bulk density, affected by soil management, and pH_w, with depth. Soil structure was generally blocky, at both soil depths, and showed a characteristic cracking due to the presence of expansible clay minerals (smectite) typical of soils in Campiña[29]. Soil texture ranged from loam to clay, with a predominance of clay-loam (USDA classification[30]), with the sampled areas displaying no differences in particle-size fractions between the two soil depths.

Table 2. Characteristics of the organic olive orchards studied, as per soil-management system (mean values ± standard error).

Organic olive orchard characteristics	Soil-management system		ANOVA
	Tillage	Mowing	*P*-value
Farm area (ha)	12.4 ± 3.1	11.4 ± 2.5	0.787
Olive fruit yield (kg ha^{-1} yr^{-1})[1]	3354 ± 719	2906 ± 370	0.586
Olive tree density (tree ha^{-1})	99 ± 10	113 ± 16	0.492
Tree crown cover (%)	27.4 ± 2.3	22.1 ± 2.8	0.158
Tree crown volume (m^3 tree^{-1})	69.8 ± 6.9	61.9 ± 14.5	0.631
Slope steepness (%)	21.0 ± 1.9	18.4 ± 1.2	0.257
Vegetative ground cover (%)[2]	9 ± 2	61 ± 4	0.000
Stone ground cover (%)	11 ± 5	11 ± 1	0.948

[1] Average, years 2003–05.
[2] Measured in spring.

Bulk density values were significantly lower in the surface layer of tilled orchards. The mowed olive orchards were significantly more compacted than the tilled orchards or the U areas at the two soil depths (Tables 3 and 4). The water-stable (WS) macroaggregate values were high, with a trend towards higher values in the U areas. This high stability of the WS-macroaggregates, and the developed soil structure observed in the field, are correlated with the high values of K_s for these soil textures[23], which were much higher in the U areas compared with the olive orchards. AWC was higher in the U areas (at both soil depths) with similar values between the T and M orchards. Olive orchards had an AWC average value (0–20 cm depth) of 0.18 and 0.17 m m^{-1} for T and M soil management, respectively, while U areas showed higher values of 0.23 m m^{-1} (Tables 3 and 4).

Organic C content in soil was clearly affected by the soil management system. Average organic C contents in the olive orchards were 19 and 39 g kg^{-1} in the top 10 cm of soil, and 10 and 12 g kg^{-1} in the sub-surface layer, for T and M soil management, respectively, which were lower values than those measured in the U areas (62 and 31 g kg^{-1}, in surface and sub-surface layer, respectively). As a result, the average values of SOC stock in the top 20 cm of soil were 31 and 74% of that in the U areas for

Table 3. Physical and chemical soil surface properties (0–10 cm depth) in organic olive orchards under current soil management systems and in U areas in Campiña (southern Córdoba), (mean values ± standard error for the two soil types combined). Different letters within a row indicate significant differences (Fisher's LSD test; $P<0.05$).

Parameters	ANOVA *P*-value[1]		Soil management system		
	Soil	Manag.	Tillage	Mowing	Undisturbed
Physical parameters					
Bulk density ($g cm^{-3}$)	0.412	0.000	0.99 ± 0.03 c	1.52 ± 0.04 a	1.10 ± 0.03 b
Clay (%)	0.236	0.641	35.9 ± 4.1 a	33.5 ± 2.2 a	31.4 ± 1.6 a
Sand (%)	0.570	0.109	16.5 ± 2.4 b	25.1 ± 3.2 a	20.8 ± 3.3 ab
Fine sand (%)	0.658	0.318	3.8 ± 0.3 a	5.4 ± 1.4 a	3.4 ± 0.6 a
WS-microaggregate ($g kg^{-1}$)	0.600	0.082	0.087 ± 0.012 a	0.055 ± 0.008 b	0.063 ± 0.011 ab
WS-macroaggregate ($g kg^{-1}$)	0.344	0.070	504 ± 40 ab	472 ± 40 b	614 ± 16 a
K_{erod} ($t h (MJ mm)^{-1}$)	0.400	0.160	0.033 ± 0.004 a	0.027 ± 0.002 a	0.024 ± 0.002 a
K_s ($mm h^{-1}$)	0.202	0.001	86.7 ± 28.3 b	54.2 ± 10.5 b	365 ± 80 a
AWC ($m m^{-1}$)	0.788	0.000	0.196 ± 0.006 b	0.188 ± 0.008 b	0.252 ± 0.014 a
Chemical parameters					
Organic C ($g kg^{-1}$)	0.818	0.000	18.6 ± 3.6 c	39.2 ± 5.4 b	61.6 ± 7.5 a
Organic N ($g kg^{-1}$)	0.778	0.000	1.7 ± 0.3 c	3.5 ± 0.5 b	5.6 ± 0.6 a
Extractable P ($mg kg^{-1}$)	0.206	0.634	8.8 ± 2.3 a	13.0 ± 4.2 a	10.6 ± 2.3 a
Exchangeable K ($mg kg^{-1}$)	0.300	0.401	366 ± 49 a	285 ± 48 a	284 ± 49 a
CEC ($cmol kg^{-1}$)	0.874	0.046	20.6 ± 1.9 ab	17.3 ± 1.3 b	25.4 ± 3.3 a
pH (H_2O)	0.547	0.703	8.36 ± 0.05 a	8.41 ± 0.06 a	8.34 ± 0.05 a
pH (KCl)	0.228	0.257	7.50 ± 0.06 a	7.62 ± 0.04 a	7.48 ± 0.11 a
C:N ratio	0.446	0.863	10.8 ± 0.4 a	11.0 ± 0.4 a	11.2 ± 0.6 a
SOC (kg organic C m^{-2})	0.841	0.000	1.86 ± 0.37 b	5.93 ± 0.78 a	6.78 ± 0.86 a

[1] *P*-value for separate one-way ANOVA for soil-type and soil-management system factors.

T and M olive orchards, respectively (Tables 3 and 4). Nevertheless, values of organic C content in T orchards were in the upper range of the values reported for rain-fed agricultural soils in the same study area[29] and for traditional olive groves in the region[31]. Organic N content in soil followed a similar pattern to that of organic C (Tables 3 and 4). Organic N content in soils in olive orchards was in the medium range of values recommended for olive cultivation[32]. The C:N ratio was within normal values (9–12) for agricultural soils[33], with no differences between soil management systems. There were no differences in extractable P and exchangeable K content among the U, M and T areas. Extractable P content was lower than recommended values for olive cultivation in soils of a similar texture[32,34], while exchangeable K content was within recommended values for olive farming in soils with high clay content[32,34]. CEC values were in the adequate range for agricultural soils with high clay content[34], with U areas having higher values (Tables 3 and 4).

Biological activity (microbial respiration and bacterial populations) were higher in the M orchards compared with the T orchards and U areas (Table 5). This could be influenced by the mowing operations in M orchards, carried out 6–7 weeks before sampling, and by subsequent decomposition of weed residues, left on the soil surface, by soil micro-organisms. Soil microbial respiration and bacterial populations were linearly correlated ($P<0.001$). Functional microbial diversity values (Shannon index, H′) ranged from a maximum of 4.42 to a minimum of 4.02, with no differences due to soil management (Table 5).

Results (eigenvalues) from the PCA showed that the first two PCs explained over 50% of the variance of total data set (PC1: 28.1%; PC2: 22.7%) (Fig. 1). The first PC (PC1) separated T from M orchards and U areas (ANOVA *P*-value <0.005), (U = M > T), and was composed of soil chemical properties (organic C and N contents, and SOC stock; Tables 3 and 6), which were affected by the soil management system. This separation at the farm level reflects differences in soil properties related to SOC stock, which had higher loads in PC1 (Table 6). These values tended to be higher in the U areas, and lowest in the T orchards (Table 3). However, there was a relatively high variability from farm to farm within the same soil management system, probably reflecting specific farm conditions such as differences in topography, soil management and farming practices or previous management history in that particular farm. There were no significant soil type effects on PC1 scores. PC2 included soil properties that related to soil parent materials (i.e., sand content and associated AWC, pH_{KCl} and CEC; Table 6) and was also affected by soil management (Table 3). PC2 scores showed significant differences ($P<0.005$) between farms due to soil management system (U = T > M; Fig. 1), reflecting management system effects on some physical and chemical soil

Table 4. Physical and chemical soil sub-surface properties (10–20 cm depth) in organic olive orchards and in U areas evaluated in Campiña (southern Córdoba), (mean values ± standard error for the two soil types combined). Different letters within a row indicate significant differences (Fisher's LSD test; $P < 0.05$).

	ANOVA *P*-value[1]		Soil-management system		
Parameters	**Soil**	**Manag.**	**Tillage**	**Mowing**	**Undisturbed**
Physical parameters					
Bulk density ($g cm^{-3}$)	0.069	0.000	1.39 ± 0.03 b	1.54 ± 0.05 a	1.20 ± 0.04 c
Clay (%)	0.837	0.640	37.3 ± 3.1 a	35.6 ± 2.2 a	33.5 ± 2.0 a
Sand (%)	0.329	0.095	14.4 ± 2.2 b	22.3 ± 2.5 a	20.4 ± 3.8 ab
Fine sand (%)	0.868	0.277	3.1 ± 0.4 a	4.4 ± 0.7 a	3.9 ± 0.6 a
WS-microaggregate ($g kg^{-1}$)	0.352	0.137	0.121 ± 0.022 a	0.073 ± 0.012 a	0.077 ± 0.023 a
WS-macroaggregate ($g kg^{-1}$)	0.902	0.013	514 ± 32 a	403 ± 34 b	557 ± 34 a
K_{erod} ($t h (MJ mm)^{-1}$)	0.681	0.142	0.034 ± 0.004 a	0.031 ± 0.002 a	0.024 ± 0.003 a
AWC ($m m^{-1}$)	0.412	0.000	0.163 ± 0.004 b	0.148 ± 0.004 b	0.202 ± 0.014 a
Chemical parameters					
Organic C ($g kg^{-1}$)	0.202	0.000	9.7 ± 2.4 b	12.2 ± 0.8 b	31.3 ± 6.9 a
Organic N ($g kg^{-1}$)	0.235	0.001	1.0 ± 0.2 b	1.2 ± 0.1 b	2.9 ± 0.7 a
Extractable P ($mg kg^{-1}$)	0.758	0.280	4.4 ± 1.5 a	5.4 ± 1.0 a	8.8 ± 3.5 a
Exchangeable K ($mg kg^{-1}$)	0.048	0.504	230 ± 34 a	175 ± 30 a	192 ± 49 a
CEC ($cmol kg^{-1}$)	0.160	0.195	19.8 ± 2.1 a	16.1 ± 1.0 a	22.6 ± 4.5 a
pH (H_2O)	0.866	0.723	8.46 ± 0.05 a	8.52 ± 0.04 a	8.50 ± 0.08 a
pH (KCl)	0.074	0.503	7.49 ± 0.06 a	7.60 ± 0.04 a	7.53 ± 0.15 a
C:N ratio	0.197	0.120	9.5 ± 0.4 b	9.9 ± 0.4 ab	11.0 ± 0.6 a
SOC ($kg OC m^{-2}$)	0.124	0.002	1.36 ± 0.34 b	1.86 ± 0.10 b	3.68 ± 0.74 a

[1] *P*-value for separate one-way ANOVA for soil-type and soil-management system factors.

Table 5. Biological soil surface properties (0–10 cm depth) in organic olive orchards under current soil management systems and in U areas in Campiña (southern Córdoba province), (mean values ± standard error for the two soil types combined). Different letters within a row indicate significant differences (Fisher's LSD test; $P < 0.05$).

	Soil-management system		
Parameters	**Tillage**	**Mowing**	**Undisturbed**
Soil microbial respiration ($mg CO_2 kg^{-1} day^{-1}$)	162 ± 24 b	604 ± 141 a	237 ± 54 b
Bacterial population [$(cfu g^{-1}) \times 10^{-3}$]	360 ± 108 b	3415 ± 1628 a	234 ± 29 b
Soil microbial functional diversity (H′)	4.23 ± 0.03 a	4.28 ± 0.03 a	4.23 ± 0.05 a

properties related to soil fertility and productivity (e.g., AWC and CEC). However, it was not possible to separate effects based on the two soil types ($P > 0.5$) (Fig. 1), due to the similarity between both soil types in the sampling areas in this study (Table 3).

Discussion

Olive orchard characteristics

The organic olive orchards studied in Campiña presented similar productivity as the average of conventionally managed, rain-fed olive groves in the area, with the T orchards presenting a numerically higher average yield ($3354 kg ha^{-1} yr^{-1}$), which was not statistically significant. The amount of water transpired by the olive trees is the key factor that determines the yield of rain-fed olive groves in this region[35]. Thus, organic farmers in the study area have been able to increase soil protection without increasing weed competition for soil water resources, particularly when weeds are left to grow during the rainy, cold season (autumn–winter), when ETo is low and soil surface remains wet for a considerable number of days. This mitigates the differences between soil water use by the weeds and that directly evaporated from the soil surface in the unvegetated areas. Studies in Andalusia have shown that olive groves with a vegetative cover tended to have greater potential to reduce run-off losses[36,37], due to increased surface roughness and a higher infiltration rate due to greater effective macroporosity. Thus, organic olive yields in Campiña suggest that conventional rain-fed olive orchards that are at a

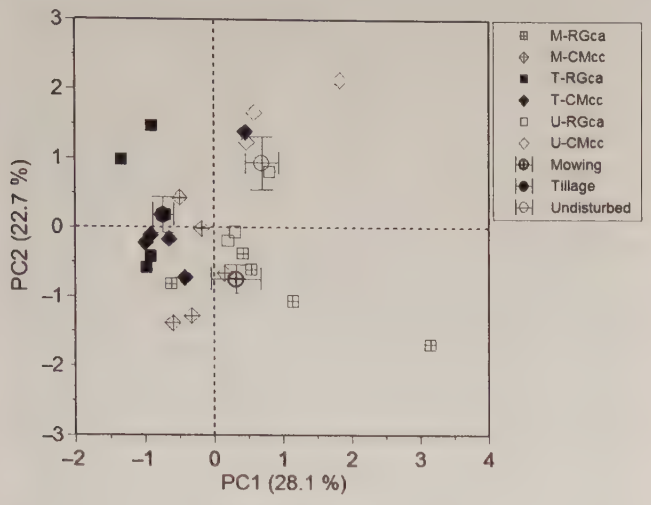

Figure 1. Soil-management and soil-type effects on the first and second principal components (PC1 and PC2) derived from standardized PCA using overall data sets for topsoil (0–10 cm depth). Symbols represent the PC scores of individual olive orchards (T or M) or U areas located in the Calcaric Regosol (RGca) and Calcic Cambisol (CMcc) soil types. Circles show mean scores for each soil management or soil use, and bars represent the standard error of the mean.

similar production level, should consider shifting from herbicide-based weed management to a soil management system based on a vegetative cover during autumn and winter, without incurring yield losses. Nevertheless, further studies in different bioclimatic areas in the region are required to validate that hypothesis for each area, and to develop the technical advice that should be provided to the farmers to prevent excessive weed growth in early spring.

Soil properties

The T orchards studied had a lower SOC level, possibly associated with increased weed biomass in the M orchards, and the acceleration of the mineralization of the soil organic matter (SOM) caused by tillage. Nevertheless, in the T orchards, the organic C content was higher than the minimum levels in the topsoil of olive groves recommended by the regional authorities to prevent severe soil degradation (1% SOM, or 5.8 g kg^{-1} organic C)[38]. The organic C measured in the soil surface (0–10 cm depth) of the T orchards (19 g kg^{-1}; Table 3) was much higher than traditional rain-fed olive orchards with a soil management based on conventional tillage (10 g kg^{-1}), or bare soil from herbicide use (6 g kg^{-1}), in a similar olive-growing area of Andalusia[39]. However, soil organic C and N content in the organic olive orchards (even in the M orchards) was less than the U areas. The organic olive orchards studied maintained high WS-macroaggegate values regardless of soil management system. This can be related to their relatively high clay content, and the relatively high organic C content for an agricultural soil

Table 6. Factor loadings for the two PCs (>50% of PC's explained variance) from standardized PCA for all soil variables measured in the topsoil layer (0–10 cm depth).

Variable or factor	PC1	PC2
Bulk density (g cm^{-3})	0.123	−0.245
Clay (%)	−0.133	0.216
Sand (%)	0.182	−0.305*
Fine sand (%)	0.184	−0.214
WS-microaggregates (g kg^{-1})	−0.262	0.099
WS-macroaggregates (g kg^{-1})	0.111	0.230
K_{erod} (t h (MJ mm)$^{-1}$)	−0.069	−0.196
K_s (mm h^{-1})	0.140	0.278
AWC (m m^{-1})	0.247	0.314*
Organic C (g kg^{-1})	0.376*	0.120
Organic N (g kg^{-1})	0.361*	0.121
Extractable P (mg kg^{-1})	0.283	−0.103
Exchangeable K (mg kg^{-1})	0.034	0.154
CEC (cmol kg^{-1})	0.127	0.373*
pH (H_2O)	−0.225	−0.145
pH (KCl)	−0.011	−0.362*
C:N ratio	0.131	0.008
SOC (kg organic C m^{-2})	0.385*	0.011
Microbial respiration (mg CO_2 kg^{-1})	0.251	−0.237
Bacterial population (cfu g^{-1})	0.276	−0.203
Microbial functional diversity (H′)	0.092	−0.162

* Variables are considered significant for loadings > |0.3|.

under Mediterranean conditions. This also indicates a high resilience for the type of tillage performed in the organic olive orchards studied. The olive orchards also showed relatively high K_s values due to high WS soil aggregates. The organic olive orchards maintained similar (T orchards) or higher (M orchards) values of microbial respiration rates, soil bacterial populations and functional microbial diversity than those measured in the U areas. Thus, comparison with the U areas suggests that overall the soil management systems maintained in the organic orchards (either M or T) has helped to preserve the biological activity of these soils under olive farming.

Sustainability of traditional olive groves

The evaluation of soil properties in organic olive groves can provide some insight into the potential for conventional olive groves located in the same landscape that have started cover-crop-oriented soil management to increase their soil quality. In Andalusia, more than half of the olive groves are located on slopes less than 15%[3], and are therefore not subjected to the compulsory CAP regulations. A significant reluctance to extend cover crop management in olive groves in the less steep areas, as well as some open questions about its viability, especially on intensive farms, remain in the region. In the olive orchards located in areas steeper than 15%, the compulsory implementation under CAP regulations[40,41] of permanent cover crop management can result in a significant increase in soil organic C content, compared with

the compulsory alternative of conservation tillage management, or soil management based on herbicides[39]. This modification of soil management should also result in a significant decrease in soil losses by water erosion, one of the objectives of such implementation. Although not addressed in this study, the results obtained in other modeling and experimental studies in olive orchards in Andalusia[4,37] indicated that soil erosion rates at hill-slope scale can be reduced to 28 or 12% for M and T management systems described in this study, respectively, compared with bare soil management based on year-round tillage. The results obtained in this study suggest that tillage can be used occasionally between early spring and early autumn to control weed growth without severe erosion. Further studies aimed at improving soil erosion estimations in the study area are needed to reduce uncertainty over erosion predictions, and, therefore, any discussion about the long-term sustainability of organic olive farming in the area.

Although the environmental sustainability of Andalusian olive groves has to be through the adoption of sustainable soil management practices, in the endeavors to prevent soil loss and soil degradation, these alternative managements could contribute to the reduction of non-renewable energy consumption. The total energy invested in weed control practices in traditional rain-fed olive groves was around 5.65 and 5.32 $GJ\,ha^{-1}\,yr^{-1}$ for conventional and organic olive groves, respectively[25]. Energy consumption in each mechanical operation for weed control (T or M) reached 1.29 $GJ\,ha^{-1}$ (1.17 $GJ\,ha^{-1}$ of fuel consumption), in organic olive farms in this study. Therefore, the adoption of soil management systems that reduce the number of mechanical operations in the olive groves, as presented in this study (non-inverting-shallow T and mechanical M), could also reduce the consumption of non-renewable fossil-fuel energy, which in turn would be an additional contribution to the environmental sustainability of traditional olive groves in Andalusia.

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Short- and full-season soybean in stale seedbeds versus rolled-crimped winter rye mulch

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Abstract

Stale seedbeds are used by organic growers to reduce weed populations prior to crop planting. Rye mulches, derived from mechanically killed (rolled and crimped) winter rye cover crops, can serve the same purpose for spring-planted organic crops. Both methods can also be employed by conventional growers who face looming problems with herbicide resistant weeds. The objective of this research was to compare these methods over 2 years in central Minnesota in terms of weed seedling emergence, populations, biomass and manual-weeding times, as well as stands and yields of short-season and full-season soybean varieties planted late, in mid June. Rye mulch greatly lowered both pre- and post-planting weed populations of common annual weeds, which substantially affected necessity for augmented weed control. For instance, the need for within-crop manual-weeding was low for soybean planted into rye mulch (0–6 h ha^{-1}), but ranged from 15 to 66 h ha^{-1} of labor for soybean planted in stale seedbeds and augmented by inter-row cultivation. However, rye mulch lowered soybean yield potential by 800–1000 kg ha^{-1} compared with stale seedbeds in 1 of 2 years. With organic feed-grade soybean seed valued at \$1 kg^{-1}, conventional soybean seed at \$0.5 kg^{-1}, and labor for manual-weeding at \$10 h^{-1}, the use of rye mulch compared with stale seedbeds augmented by manual-weeding are equally rational choices for organic growers in central Minnesota (assuming labor is available for hand-weeding), but rye mulches probably would be a wise financial option for conventional growers compared with hand-weeding. Lastly, full-season soybean had higher yields than short-season soybean and probably represents a prudent selection in central Minnesota, regardless of the late planting date requirements for both the rye mulch and stale seedbed systems.

Key words: cover crop, false seedbed, hand-weeding, late planting, organic, weed control

Introduction

Management of arable weeds without the assistance of modern synthetic herbicides is difficult, but sometimes necessary. For instance, where weeds have evolved resistance to herbicides, periodic interjection of non-chemical methods of weed management may be indispensable for sustaining cropping systems otherwise wholly dependent upon herbicides[1]. In addition, non-chemical methods are compulsory for organic systems. Moreover, weed control is the major agronomic concern of most organic growers[2,3].

Organic growers employ a wide range of methods to manage weeds [4,5]. Among the many methods are two 'pre-emergence' weed control tactics that can be used for spring-planted crops: stale (or false) seedbed technique and winter cover crops. Stale seedbeds are a long-established practice that can be used with supplemental herbicides in conventional systems[6] or without them in organic systems[4]. For example, spring weed populations emerging in previously cultivated soil are killed through subsequent cultivations prior to crop sowing. The stale seedbed could be prepared weeks or even months ahead of time (e.g., the previous autumn) to encourage the spring flush of weeds prior to actual crop planting. Weed control typically improves appreciably with later cultivations in spring, but subsequent crop yield tends to decline with these late planting dates[7]. Thus, a balance must be reached between low weed populations and high crop yield in terms of successful application of the stale seedbed technique[8]. Additional issues with stale seedbed management are that repeated soil cultivations cause commensurate losses in arbuscular mycorrhizae in soil[9] as well as soil organic matter and soil structure[10], and soil particles through water and wind erosion.

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Cover crops, specifically winter rye (*Secale cereale* L.), for weed control in temperate regions have gained considerable popularity recently[11], partly due to the advent of roller-crimpers used to terminate their growth effectively in spring[12–17]. A winter rye cover crop has several attributes. First, it is extremely cold-hardy, which allows for reliable over-winter survival in north temperate regions, such as Minnesota, where winter air temperatures of −20°C commonly occur. Second, seed costs for vigorous and well-adapted varieties are modest, as little as US$50 ha^{-1}. Third, the plant grows lushly in early spring and inhibits weed seed germination and/or weed seedling establishment. Fourth, winter rye can be killed by mechanical means relatively easily at or just after anthesis. If done properly, the kill rate is nearly 100% and, thus, little resprouting or retillering occurs. Fifth, some summer crops, such as soybean, are relatively insensitive to leachates from decomposing winter rye residues, which may be inhibitory to other species, and fix their own nitrogen, which overcomes nitrogen immobilization caused by lushly growing rye. Sixth, winter rye cover crops have positive environmental characteristics, including sequestration of carbon and many labile soil nutrients, as well as inhibition of soil erosion.

Cover crops also have disadvantages. The major drawback of using winter rye as a cover crop is that its growth termination by mechanical methods must be delayed until anthesis. Anthesis usually does not occur until early to mid June in Minnesota, which means that relatively short-season soybean varieties (< 1.0 RM, relative maturity) with inherently lower yield potentials, must be planted in rye mulch. Traditional planting dates without cover crops for full-season soybean (≥ 1.0 RM) in this region are early to mid May. Moreover, regardless of the late planting date, rolled and crimped rye mulch by itself may impose a yield penalty on soybean, either directly or through reduced stand establishment. At lower latitudes (≤ 43°N) such as southern Wisconsin, central Illinois and central Pennsylvania, these penalties range from nil to about 20% of soybean yield[12,13,15,18]. In North Carolina, yield penalties across five site-years were 0, 4, 5, 19 and 57%[17], with the latter value likely due to failure of the rye mulch to control weeds rather than a direct effect of rye mulch on soybean. In contrast, where growing seasons are longer, such as in Alabama, rolled and crimped winter rye mulches may provide yield rewards for soybean compared with conventional plantings[16]. How soybean responds to rolled and crimped rye mulches in the extremely short growing seasons of the northern Great Plains (≥ 45°N) is not known.

Objectives of the current project were to compare stale seedbeds with roller-crimper terminated winter rye cover crops with regard to (i) pre- and post-plant weed seedling dynamics and end-of-season weed biomass, (ii) hand-weeding labor requirements, (iii) soybean stands and yields, and (iv) cursory calculations of economic returns for a north temperate region such as west central Minnesota. The null hypothesis is that the aforementioned variables do not differ between stale seedbed and cover crop systems; whereas the alternative hypothesis is that a rye cover crop suppresses weeds so effectively that it may be a superior method compared with the stale seedbed approach.

Materials and Methods

Field site

Two identical experiments were performed at the Swan Lake Research Farm, Stevens County, MN (45°41′N, 95°48′W) in 2010 and 2011. Separate fields, less than 100 m apart, were used each year. Soil type was a Barnes loam (fine-silty, mixed, super-active, frigid Calcic Hapludoll) with a pH of 7.3, and sand, silt, clay and organic matter contents of about 41, 33, 25 and 6%, respectively. Camelina (*Camelina sativa* [L.] Crantz) was the previous crop in 2009 and soybean (*Glycine max* [L.] Merr.) in 2010.

Experimental design and winter rye management

Each experiment followed a randomized split plot design[19] with four replications. Main plots comprised stale seedbed versus rye mulch treatments, and split plots involved intense or lax weed control, as detailed below.

For every experiment, a section of a field was partitioned into eight plots arranged in four blocks. Each plot was 6 m wide and 12 m long. One plot in each block was sown to winter rye ('FS Hi-Rye 500' on September 2, 2009 and September 20, 2010) at 73 kg ha^{-1} in rows spaced at 20 cm. These plots constituted the 'rye mulch' treatment. The remaining plots were field-cultivated and fallowed over winter. These represented the 'stale seedbed' treatment. The entire area was fertilized with 112 kg N ha^{-1} in the form of ammonium nitrate, which was incorporated with a field cultivator, immediately prior to sowing rye to eliminate N nutrition as a source of variation.

Heights of representative winter rye plants were measured at four random locations in each block at weekly intervals beginning in early May. Winter rye biomass was estimated by clipping all plants at ground level in two randomly placed 0.5 m^2 quadrats in each block at the time that growth was terminated (June 9, 2010 and June 14, 2011). Samples were weighed immediately to determine fresh weight and then dried for one week at 50°C to determine dry weight. At the time of sampling, plants were in the post-anthesis stage, which was about 1 week after they had reached their maximum heights. Anthers extruded from flowers were dry and shriveled, which indicated that pollination was complete, and represented a useful rule-of-thumb for the time to terminate

growth of a winter rye cover crop in west-central Minnesota.

Weed emergence patterns before planting soybean were recorded in one randomly placed but permanent quadrat (each 0.5 m^2) in each plot of both the rye mulch and stale seedbed treatments. Seedlings were identified, counted, and removed by hand at approximately weekly intervals beginning in early May in both years.

Winter rye growth was terminated with a 3-m wide, water-filled, roller-crimper with chevron-like blades[13,20]. Rolling-crimping occurred in a single direction parallel with the rows. Preliminary rolling-crimping in border plots indicated that winter rye lodging increased with tractor speed; consequently, all winter rye cover blocks were rolled and crimped at a speed of $\geq 10\,km\,h^{-1}$. Rolling-crimping was highly effective in killing winter rye, with negligible regrowth observed.

Soybean planting and management

Soil in stale seedbed treatments was field-cultivated again and harrowed on the same dates as rolling-crimping. Such late seedbed preparation would have been expected to control large percentages of annual weeds at this site. In this region >90% of potential seedling populations of common annual weeds typically can be controlled by seedbed preparation in early to mid June compared with more traditional seedbed preparation times in late April to early May[8]. Within 1 day after roller-crimping or field-cultivation, soybean was sown with a John Deere MaxEmerge no-till planter at 387,000 seeds ha^{-1} in rows spaced 76 cm apart. (The use of trade names does not imply product endorsement by USDA.) For comparison, target planting dates for conventional soybean (1.0 RM) are early to mid May in this area.

Both short- and nearly full-season varieties were tested each year. The short- and full-season soybeans were planted in contiguous but separate and non-randomized plots, and therefore, they were treated as separate experiments. The short-season variety was Croplan RT0043 (0.04 RM) both years; and the full-season variety was NK S08 M8 (0.8 RM) in 2010 and Croplan 970 (0.9 RM) in 2011. The plots were 12 m long and 6 m wide (8 rows), and within each a 4-row subplot was assigned randomly to either of two weed management treatments: lax (little or no additional weed control) or intense (augmented weed control). For augmented weed control in stale seedbed plots, ethalfluralin was applied at 0.6 kg ai ha^{-1} and incorporated with a spring tine harrow. In addition, inter-row areas of all stale seedbed plots were cultivated once in mid July. Hand-weeding supplemented the herbicide-treated and cultivated stale seedbed subplots, and it was the sole form of additional weed control in the augmented rye mulch plots. Hand-weeding included both hand-pulling and hoeing with long-handled hoes. Amounts of time spent hand-weeding were recorded. Decisions of whether or not to hand-weed a plot were made by two technicians with about 40 years of combined experience in research on soybean–weed interactions. Decisions were subjective and were meant to mimic those of hand-laborers hired by growers.

In summary, each soybean experiment had the following treatments: (1) stale seedbed (stale seedbed augmented by inter-row cultivation), (2) stale seedbed plus (stale seedbed augmented with ethalfluralin, cultivation, and hand-weeding), (3) rye mulch (winter rye mulch only), and (4) rye mulch plus (winter rye mulch augmented by hand-weeding).

Weed monitoring

Weed emergence patterns after planting were estimated by permanently and randomly positioning two 0.5 m^2 quadrats in each augmented subplot of the short-season soybean only, and identifying, counting, and removing all weed seedlings at approximately weekly intervals beginning immediately after soybean planting and continuing through September. Quadrats were lifted and replaced immediately before and after inter-row cultivation events in the stale seedbed plots. Weed biomass was determined on September 22, 2010 and September 28, 2011 by clipping all weeds at ground level within a 0.5 m^2 quadrat (0.5×1.0 m) that was perpendicular to and spanned the central two soybean rows in each subplot of the short-season soybean.

Soybean yield was determined by harvesting the central two rows of short- and full-season soybean in each subplot with a plot combine on October 6 and 12, 2010 (prior to the first killing frost of autumn) and October 4 and 7, 2011 (after the first killing frost on September 14). Seed yield samples were cleaned of chaff and other debris, seed moisture determined (via a capacitance meter), weighed, sample weights adjusted to 13% seed moisture and unit-area yields calculated. Soybean stand was determined by counting cut stems in two 1-m lengths of row in each subplot immediately after harvest.

Statistical evaluations

Statistical evaluations included preliminary analysis of variance (ANOVA) that considered the soybean establishment method (rye mulch versus stale seedbed) and weed management (intense versus lax) as fixed effects and block (four replications) and year (2010 and 2011) as random effects. Year effects were always highly significant ($P < 0.01$) and, consequently, yearly data were examined separately using the split plot procedure available in Statistix 9 software[19], with the establishment method as the main factor and weed management as the sub factor. Tukey's HSD was used to compare treatment means at $P = 0.05$ or 0.10. Lastly, linear regression was used to explore the relationship between soybean stand density and soybean yield.

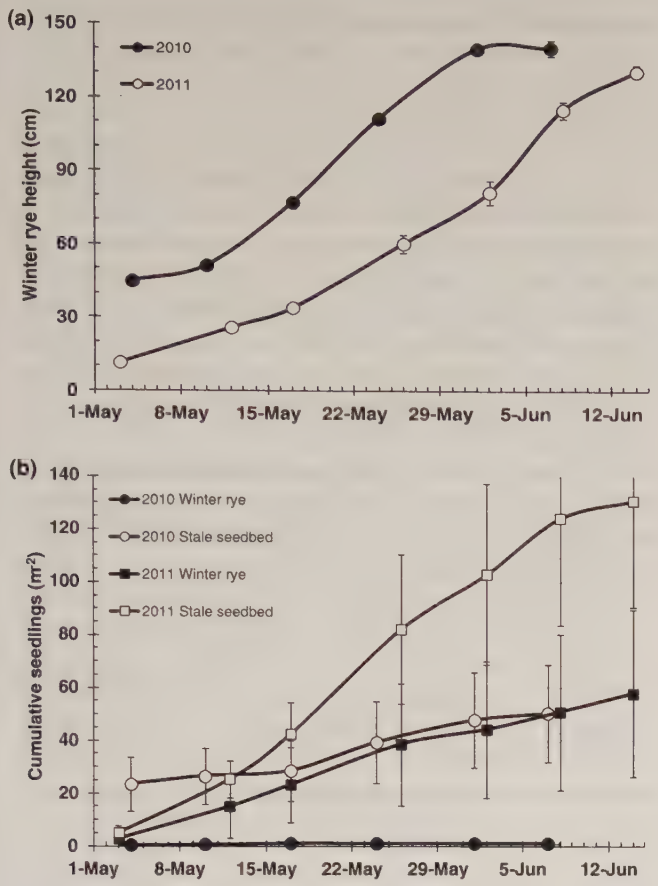

Figure 1. (a) Increase in height of winter rye during May and June 2010 and 2011, with growth terminated by rolling and crimping on June 9, 2010 and June 14, 2011. (b) Cumulative emergence of weed seedlings prior to soybean planting in a winter rye cover crop and a stale seedbed during spring of 2010 and 2011. Vertical bars represent standard errors.

Results

Winter rye growth

Winter rye growth (Fig. 1a) probably was delayed in spring 2011 compared with 2010 because of the late snow-melt and abnormally low temperatures. Although winter rye grew rapidly during May each year, the cover crop was more vigorous in 2010 than 2011. Height, fresh weight, and dry weight (±SE) of winter rye at termination with a roller-crimper on June 11, 2010 were 141 ± 3.3 cm, 26 ± 3.6 Mg ha^{-1} and 6.0 ± 1.04 Mg ha^{-1}; and on June 14, 2011 these same variables were 131 ± 2.6 cm, 22 ± 3.9 Mg ha^{-1} and 6.0 ± 0.89 Mg ha^{-1}. The rolled and crimped winter rye created mulch on the soil surface that was 5–15 cm thick.

For comparison, dry weights of 'Hi-Rye' at the time of rolling-crimping were 6–7 Mg ha^{-1} (mid May) in central Illinois[13]; 'Rymin' winter rye was nearly 11 Mg ha^{-1} (early June) in southern Wisconsin[12] and 4.5–11 Mg ha^{-1} (May) in North Carolina[17]; and 'Aroostock' winter rye ranged from about 6 to 10 Mg ha^{-1} (early June) in central Pennsylvania[15].

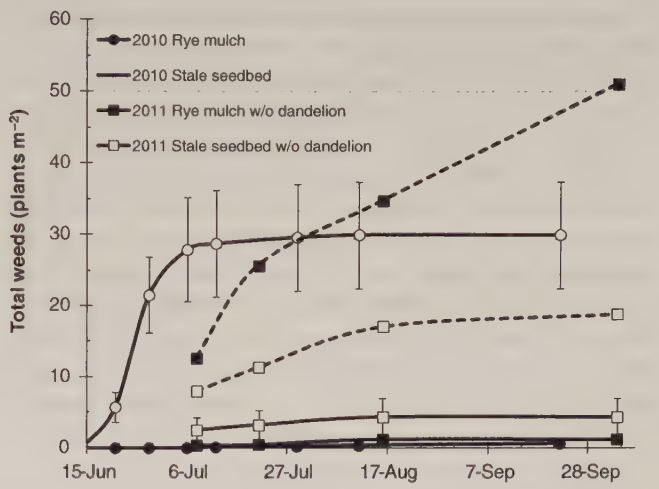

Figure 2. Cumulative emergence of all weed seedlings combined after soybean planting in winter rye mulches and stale seedbeds during summers of 2010 and 2011. In 2011, solid lines represent combined annual weeds without the perennial, dandelion, whereas the dotted lines include dandelion (77 and 98% of recorded plants in stale seedbed and rye mulch, respectively). Vertical bars represent standard errors. (For clarity, SE not included for 2011 values with dandelion.)

Weed emergence, biomass and hand-weeding

Pre-plant weed emergence was curtailed appreciably by the presence of growing winter rye (Fig. 1b). In 2010, cumulative total emergence of all weed species combined was 51 ± 18.5 plants m^{-2} in the stale seedbed system, but only 1 ± 0.3 plants m^{-2} in rye mulch. Analogous values in 2011 were 131 ± 40.5 plants m^{-2} in the stale seedbed and 58 ± 31.7 plants m^{-2} in rye mulch. Thus, winter rye provided 98% pre-plant weed control in 2010 and 56% in 2011 in terms of seedling numbers. Observations indicated that plant sizes also decreased substantially by the presence of rye mulch. The dominant weed species were eastern black nightshade (*Solanum ptycanthum* Dun.) in 2010 and redroot pigweed (*Amaranthus retroflexus* L.) in 2011. Nightshade and pigweed represented 60 and 12% of the total pre-plant weed population of the stale seedbed system in 2010 and 4 and 50% in 2011. The presence of rye mulch decreased pre-plant densities of these two species by ⩾ 82%. Nightshade control is especially critical in organic systems in terms of nightshade berry and seed contamination and pigment staining of soybean seed at harvest.

Post-plant weed emergence patterns were affected by the presence of rye mulch, but in contrasting manners during the 2 years (Fig. 2). In 2010, about 30 ± 7.5 plants m^{-2} emerged in the stale seedbed system compared with only 1 ± 0.3 plants m^{-2} in rye mulch. Emergence was complete by mid July. Half of the plants in the stale seedbed system comprised annual weeds common to the research farm: nightshade, pigweed, common lambsquarters (*Chenopodium album* L.) and foxtails (*Setaria* spp.). The remaining plants were dandelion (*Taraxacum officinale*

Weber). Pigweed and dandelion evenly represented the few plants that emerged in rye mulch.

The pattern of emergence in 2011 began later and continued longer than in 2010 and, surprisingly, densities were higher in the rye mulch than in the stale seedbed system (Fig. 2). The stale seedbed system supported 19 ± 8.2 plants m^{-2} whereas 51 ± 46.4 plants m^{-2} emerged in the winter rye mulch. About 23% of the plants in the stale seedbed system were pigweed, lambsquarters and foxtail and the rest were dandelion. In contrast, 97% of the plants in the rye mulch were dandelion, the rest being an even mixture of foxtail, lambsquarters, nightshade and pigweed. The early growing season (May through July) of 2011 was moist (315 mm rain) compared with that of 2010 (182 mm rain), which allowed dandelion to reproduce vigorously over spring and summer throughout the general area. The rye mulch probably trapped many wind-blown dandelion seeds, which lack dormancy[21], during that time and created an excellent seedbed for them to germinate immediately. Excluding dandelion from the calculations, then post-plant annual weed emergence was 4.4 ± 2.61 and 1.3 ± 0.66 m^{-2} in the stale seedbed and rye mulch treatments, respectively (Fig. 2), which proportionally reflects the results in 2010.

Weed biomass (dry weight) at the end of the 2010 growing season was influenced substantially by the establishment method (main factor, $P = 0.04$), weed management (sub factor, $P = 0.01$) and interactions between these two variables ($P = 0.01$). Total weed biomasses in stale seedbed, stale seedbed plus, rye mulch and rye mulch plus treatments were 453 ± 131.3, 8 ± 5.6, 1 ± 1.0 and 1 ± 0.5 g m^{-2}, respectively (Tukey's $HSD_{0.05} = 308$). In contrast, at the end of the 2011 growing season, weed biomass was not influenced by the establishment method ($P = 0.48$), weed management ($P = 0.94$) or interactions ($P = 0.72$), primarily because of the high levels of dandelion that proliferated in the rye mulch plots during late summer. Nevertheless, weed biomass averaged only 35 ± 8.7 g m^{-2} across treatments in 2011, which probably was not high enough to have interfered with soybean growth and yield in any treatment.

For comparison, in Illinois total end-of-season weed biomass in soybean was reduced from about 500 g m^{-2} in stale seedbeds to < 100 g m^{-2} in rye mulch[13]. In southern Wisconsin, weed biomass in early July was reduced by 62% in rye mulch compared with stale seedbeds[12]. In central Pennsylvania, mid-summer weed biomass reduction in soybean due to rolled and crimped winter rye compared with bare soil across five site-years was 15, 53, 91, 92 and 93%[18]. Lastly, in the absence of herbicides, rolled and crimped rye in Alabama provided 58, 69 and 83% weed control over 3 years[16].

Hand-weeding

Four hand-weedings were performed in 2010 (June 29 and July 8, 19 and 29) in the stale seedbed system that was augmented with herbicide. Cumulative times (labor-hours) were equivalent to 66 ± 9.2 h ha^{-1} in the short-season soybean and a nearly identical duration of 61 ± 8.3 h ha^{-1} in the full-season soybean. No hand-weeding was needed in the rye mulch system because of the paucity of weeds. Two hand-weeding efforts were conducted in 2011 (July 25 and August 17). Cumulative labor-hours were 15 ± 6.6 and 22 ± 4.9 h ha^{-1} in the stale seedbed short- and full-season soybeans, which also received herbicide, but only 3 ± 0.2 and 6 ± 1.9 h ha^{-1} were needed in the rye mulch short- and full-season soybean treatments, which were herbicide-free. Thus, the rye mulch either eliminated or greatly reduced labor requirements for hand-weeding.

For comparison, an average hand-weeding time of 5 h ha^{-1} was reported for high-value organic soybean (*sans* cover crop) in Iowa[22], but this was only for removing weeds that overtopped the crop later in the growing season. In Ontario, Canada, hand-weeding (at \$10 h^{-1}) was the major expense for organic weed management, where costs ranged from \$92 to \$288 ha^{-1}, which represents about 8–25 h ha^{-1} of labor[23]. Hand-weeding in high-value vegetable crops may require up to 175 h ha^{-1} in New York State[24] and >200 h ha^{-1} in California[25]. The latter statistic is only for 'hand-weeding' literally (i.e., hand pulling), as hand-hoeing is considered a different class of manual labor in California.

Soybean stand

Stand densities differed between years for both short-season ($P = 0.07$) and full-season ($P < 0.01$) soybean, and there were year × establishment method interactions for both varieties ($P = 0.05$, 0.03). Consequently, stands for both varieties were analyzed separately each year. In 2010, short-season soybean stands were influenced by the establishment method ($P = 0.05$), but not weed management ($P = 0.23$) nor an establishment method × weed management interaction ($P = 0.17$). Stands averaged $335{,}000 \pm 16{,}000$ plants ha^{-1} in the stale seedbed system and $266{,}000 \pm 15{,}000$ plants ha^{-1} in the rye mulch system (Tukey's $HSD_{0.10} = 53{,}000$). In 2011, no variable or interaction influenced short-season soybean stands ($P > 0.68$). Stand density averaged $333{,}000 \pm 11{,}000$ plants ha^{-1} across treatments.

In 2010, full-season soybean stands were not influenced by the establishment method ($P = 0.23$) nor weed management ($P = 0.83$), but an interaction did exist ($P = 0.06$). Densities in stale seedbed, stale seedbed plus, rye-mulch and rye-mulch plus treatments were $291{,}000 \pm 18{,}000$, $263{,}000 \pm 18{,}000$, $214{,}000 \pm 28{,}000$, and $237{,}000 \pm 30{,}000$ plants ha^{-1}, respectively (Tukey's $HSD_{0.10} = 44{,}000$ between establishment methods). In 2011, full-season soybean stands were affected by the establishment method ($P = 0.08$), but not weed management ($P = 0.77$) nor an interaction ($P = 0.49$). In this instance, rye mulch plots had higher densities

(340,000 ± 18,000 plants ha^{-1}) than stale seedbed plots (312,000 ± 15,000 plants ha^{-1}).

In summary, treatment effects were inconsistent regarding soybean stands. The year effect probably was due to poor soil-seed contact in 2010, which was caused by incomplete closure of the soil slot created by the planter's double-disk openers. Failure of the packing wheel to close the slot was a result of wet soil conditions at planting, generally, and root-bound soil, specifically, in the rye mulch plots. Root-bound soil on the sidewalls of the slot tended not to crumble and overtop seeds, and dry weather immediately after planting inhibited exposed seeds from germinating. In 2011, the packing wheel was adjusted to facilitate better closure of the seeding slot, and plentiful rainfall after planting assured high germination rates and good stand establishment. For comparison, soybean stands in southern Wisconsin, central Pennsylvania, and North Carolina either were not affected or were influenced inconsistently by rye mulch[12,15,17].

Soybean yield

Yields differed between years for both short-season ($P<0.01$) and full-season ($P<0.01$) soybean, and there were year × establishment method interactions for both varieties ($P=0.03$ and 0.05). Consequently, yields for both varieties were analyzed separately each year. Short-season soybean yields in 2010 were influenced by the establishment method ($P=0.09$), but not by weed management ($P=0.61$) nor an establishment method × weed management interaction ($P=0.34$). Yields averaged 2560 ± 220 kg ha^{-1} in the stale seedbed system and 1770 ± 120 kg ha^{-1} in the rye mulch system (Tukey's $HSD_{0.10}=740$). In 2011, no variable or interaction influenced short-season soybean yields ($P \geq 0.72$), which averaged 1360 ± 100 kg ha^{-1}.

Full-season soybean yields in 2010 were affected by the establishment method ($P<0.01$), weed management ($P=0.08$) and an establishment method × weed management interaction ($P<0.01$). In the stale seedbed, stale seedbed plus, rye mulch and rye mulch plus treatments, full-season soybean yields averaged 2640 ± 190, 3260 ± 120, 2080 ± 110 and 1830 ± 110 kg ha^{-1}, respectively (Tukey's $HSD_{0.05}=420$). In 2011, no variable or interaction influenced full-season soybean yields ($P \geq 0.12$), which averaged 1960 ± 120 kg ha^{-1}.

For comparison, in Illinois weed-free soybean (3.0 RM) attained yields of 2200–3200 kg ha^{-1} in rye mulch compared with 2700–3800 kg ha^{-1} in bare soil, with locally late planting dates of May 24 to June 2[13]. Similarly, in Wisconsin soybean (1.0 RM) yields were about 2800 kg ha^{-1} in rye mulch and 3600 kg ha^{-1} in stale seedbeds planted late (May 18–June 17)[12]. Thus, mulch derived from rolled and crimped winter rye lowered yield potential more in 2010 in Minnesota (31–34%) than in Illinois and Wisconsin (16–22%). This geographical difference probably reflects the shorter growing season and greater aridity of western Minnesota compared with Illinois and Wisconsin. Furthermore, negative effects of rye at these locations on soybean yield would be exacerbated by late soybean planting and soil water use by winter rye.

The linear regression relationship between soybean yield and soybean stand was significant in 2010 for both short-season ($F=10.8$, $P=0.01$) and full-season varieties ($F=5.5$, $P=0.03$). However, the intensity of the relationships was modest with low r^2 values (0.43 and 0.27) and slopes of only 7 and 6 kg seed yield 1000^{-1} plants, respectively. Yield and stand were not related in 2011; corresponding statistics for short- and full-season varieties were $F=0.7$, 0.1; $P=0.41$, 0.71; $r^2=0.05$, 0.01; and slopes of 2 and 1 kg seed yield 1000^{-1} plants.

In summary, the generally lower yields in 2011 compared with 2010 probably were caused by 2011's early frost (September 14), which terminated seed maturation of both varieties prematurely. A comparably low temperature in 2010 was not reached until October 15, which was after soybean harvest. As a consequence, soybeans were able to reach their yield potentials in 2010. Similarly, the longer growing season in 2010 allowed expression of effects of the establishment method, specifically the effects of a stale seedbed (dense stands and high yields) compared with rye mulch (poorer stands and lower yields). Rye mulch sufficiently impeded weed emergence and growth that even in the weedy treatment soybean yield losses due to weed competition were not detected. In contrast, stale seedbeds without augmented weed control could have weed populations high enough to make an appreciable impact on soybean yield. Lastly, no management effects were apparent during a year with an abruptly terminated (early frost) growing season, as in 2011.

Conclusions

Both pre-plant and post-plant populations of common annual weeds were lowered appreciably by the use of winter rye mulches compared with stale seedbeds. As a consequence hand-weeding requirements were negligible (0–6 h ha^{-1}) in soybean planted into rye mulch, but ranged from 15 to 66 h ha^{-1} in stale seedbed systems. Thus, rye mulches can clearly lower hand-weeding efforts, but rye mulches also have the capacity to lower yield potential of both short- and full-season soybean, for instance by 31 and 34%, respectively, in 2010, compared with the use of stale seedbeds. These yield decreases translate into losses of about 800–1000 kg ha^{-1} of soybean seed with the use of rye mulches. Market values of feed grade soybean seeds were \$0.53 kg^{-1} (conventional) and \$1.04 kg^{-1} (organic) in mid May 2012. Thus, with winter rye as a cover crop, gross returns for soybean could be lowered by about \$500 ha^{-1} for conventional soybean and \$1000 ha^{-1} for organic soybean compared with soybean planted into stale seedbeds without rye mulch.

The use of stale seedbeds, however, potentially entails higher management costs for weed control compared with the use of winter rye cover crops. For example, in 2010 full-season soybean yield was lowered by nearly 900 kg ha^{-1} because of weeds not controlled by inter-row cultivation in the stale seedbed system. This reduction represents gross return losses of about \$450 ha^{-1} (conventional) to \$900 ha^{-1} (organic), which are comparable with the penalties imposed by the use of winter rye cover crops (see previous paragraph). If 60 h of hand labor were required to remove the offending weeds, as in 2010, and labor was valued at \$10 h^{-1}, then this input would be worth \$600 ha^{-1}. Thus, hand labor may still be a rational option for organic soybean planted in stale seedbeds (i.e., \$900 − \$600 = \$300 net gain), but less likely so for conventional soybean (i.e., \$450 − \$600 = \$150 net loss). These admittedly coarse calculations also suggest that a conventional grower in Minnesota with herbicide resistance problems would benefit more from adopting winter rye cover crops than the stale seedbed technique to manage resistant annual weeds. In contrast, the stale seedbed technique augmented by hand-weeding compared with winter rye cover crops probably is roughly equally cost-effective for organic growers in Minnesota, assuming labor for hand-weeding is available when needed. In the absence of assured availability of sufficient hand labor, the value of winter rye cover crops increases markedly.

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Book Review

Japan's Dietary Transition and its Impacts. By V. Smil and K. Kobayashi, 2012. The MIT Press, Cambridge, MA. 229 pages, US $29.00, ISBN 978-0-262-01782-4.

It is often noted by outside observers that the intricacies, formalities and idiosyncrasies of Japanese culture can befuddle even the most cosmopolitan of globetrotters. On a planet crudely organized around 'in-groups'—the West, the Muslim world, the Sino Kingdom—the Japanese represent an unusually stark example of inward-looking ethnic uniqueness, shaped by a fascinating human and natural history whose effects linger to this day. This concept of cultural inimitability rings particularly true when one analyzes the nation's foodstuffs, for Japanese cuisine is a veritable smorgasbord of culinary innovation, assimilation and diversity. In the new hardcover *Japan's Dietary Transition and its Impacts*, the perennially lucid Vaclav Smil joins forces with the University of Tokyo academic Kazuhiko Kobayashi to present a magisterial overview of the composition, complexities and gradual evolution of the Japanese diet. Adopting a characteristically macro-analytic perspective, the book touches on themes likely to be of interest to a broad category of readers, including the roots of Japan's enviable life expectancy, the health benefits of assorted Japanese food choices and the sustainability implications of the Japanese way of life.

This tome is not designed for specialists seeking detailed investigation of a specific topical area. The authors assume an all-encompassing approach, and contend in the introduction that the 'realities of more than a century of gradual but profound dietary changes with major domestic and foreign implications are of interest to many readers'. The term 'readers' in this context is explicitly generically defined; the authors say as much, noting that the material 'can be read with some profit by non-specialists who seek reliable information about a remarkable historical, economic, social, and nutritional phenomena'.

Divided into several sections, the volume mingles encyclopedic statistics with incisive facts. The material is presented clearly, with sobering but revealing statistics deployed throughout. Throughout this process, no attempt is made to idealize the Japanese food choices, which have led to, *inter alia*, nitrate leeching, marine life depletion, far-reaching land degradation and the frustration of coordinated international efforts to preserve endangered whale and tuna species. Like many holistically minded environmental books, it calls to the fore issues of which the average reader may not be aware (such as the stunning fact that over 25 billion disposable chopsticks are used in Japan every year). Other interesting discussions include exploration of virtual water imports through the outsourcing of agriculture, debunking the myths about the benefits of Japanese gastronomic exports and scrutiny of reasons potentially underlying the country's stunning longevity (epitomized in the fact that the country contains the world's largest collection of centenarians).

Faults within the text are few but, alas, make an appearance. This reviewer found the incessant use of transcribed Japanese words unduly arduous to navigate. At times, constant references to statistics can be off-putting to a more casual or layman reader (this reviewer must also admit to glazed eyes on more than one occasion), even though Smil possesses an uncanny knack for elegantly presenting back-of-the-envelope calculations[1]. Equally irksome was a recurring issue with spelling mistakes. The text would certainly have benefited from more rigorous revision; embarrassingly, even the authors' biographies were not exempt from this trend of editorial sloppiness.

Invariably, readers of this text cannot help but ask what Japan's future holds. No grandiose conjectures or assumption-laden speculations are offered here; instead, emerging developments—demographic, economic, environmental and social—are systemically analyzed. An uncertain picture is the unsatisfying result, as contradictory Japan is at once frugal yet gluttonous, precarious yet stable, and advancing yet falling. Throughout the quagmire, Smil (a scholar who is certainly no stranger to grand intellectual explorations of a given topic, e.g. Smil[2]; indeed, a country-specific analysis is a departure from his usual fare) and Kobayashi are excellent guides, and no one interested in the nexus of food and environment should look with equanimity on missing their latest comprehensive examination.

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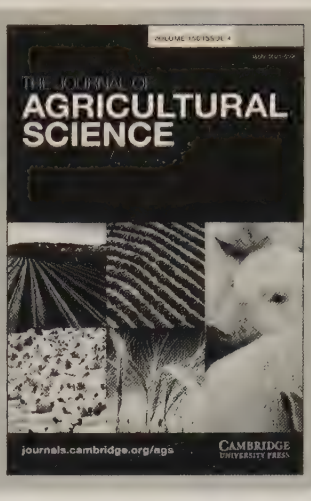

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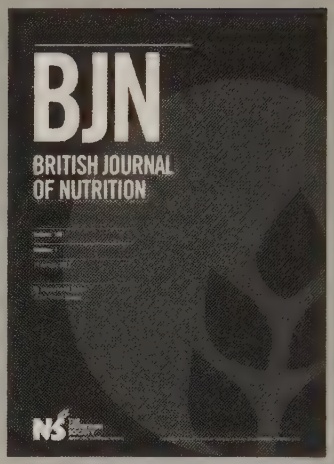

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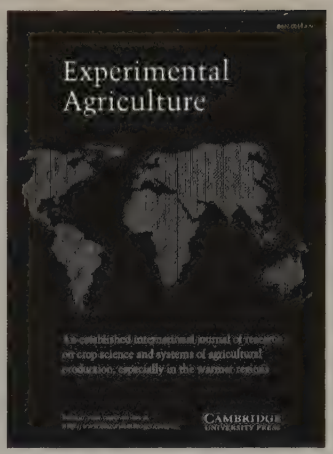

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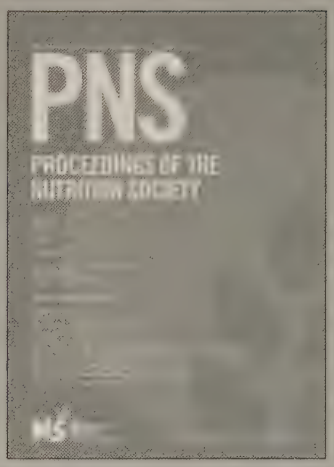

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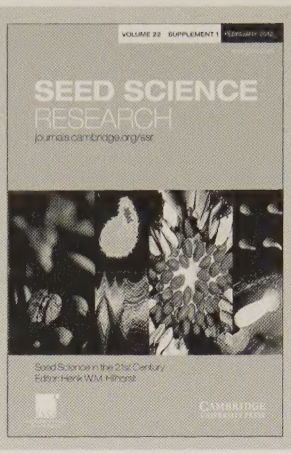

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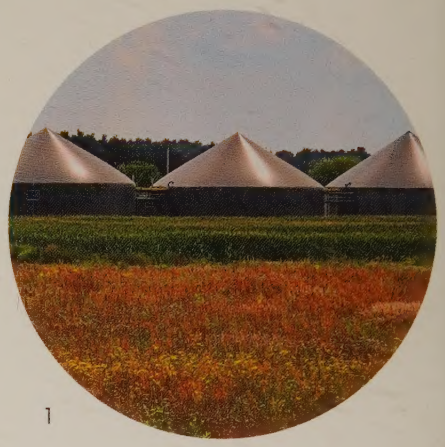

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